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The Challenge of Prognostics of Rolling Element Bearings

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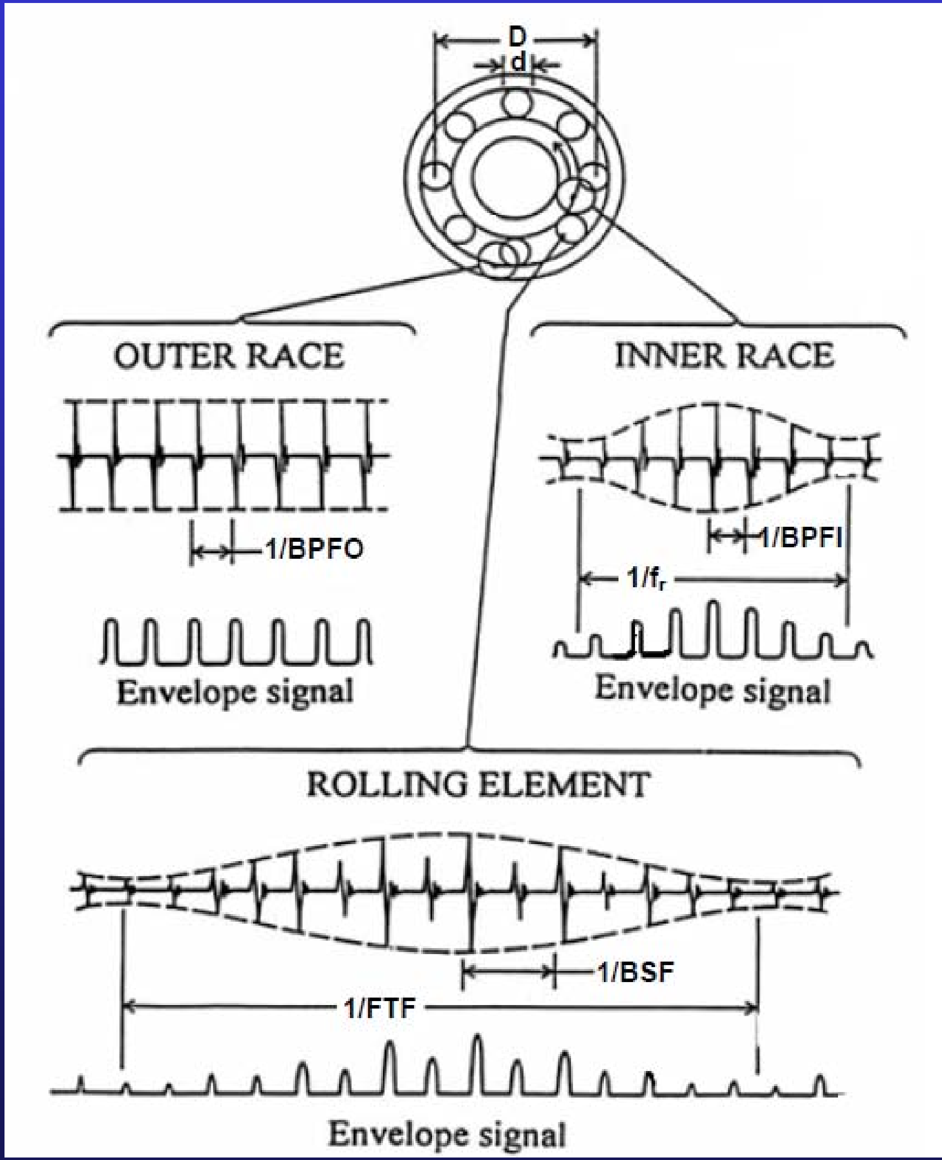
Background

- Bearing fault detection now well established, in particular for simple machines
- Even where the faulty bearing signal is strongly masked, such as in helicopter gearboxes, the bearing signals can be separated from masking signals
- Once the bearing signal is separated from masking signals, envelope analysis provides a very powerful diagnostic tool to diagnose the faults, in particular for initial local faults
- Even when faults are extended and smoothed, so that sharp impacts are less pronounced, the bearing fault can often be separated from gears by the cyclostationary properties
- Problem with prognostics is that many parameters first trend up, then down

LOCAL FAULTS IN ROLLING ELEMENT BEARINGS



Series of high frequency bursts as bearing components interact with faults.

Modulated by frequency with which the fault passes through the load zone

Envelope signal contains more diagnostic information on repetition frequencies and modulation than the raw signal, which is dominated by excited resonances

BEARING FAULT “FREQUENCIES”

$$BPFO = \frac{n f_r}{2}\left\{1 - \frac{d}{D}\cos\phi\right\}$$ Outer race

$$BPFI = \frac{n f_r}{2}\left\{1 + \frac{d}{D}\cos\phi\right\}$$ Inner race

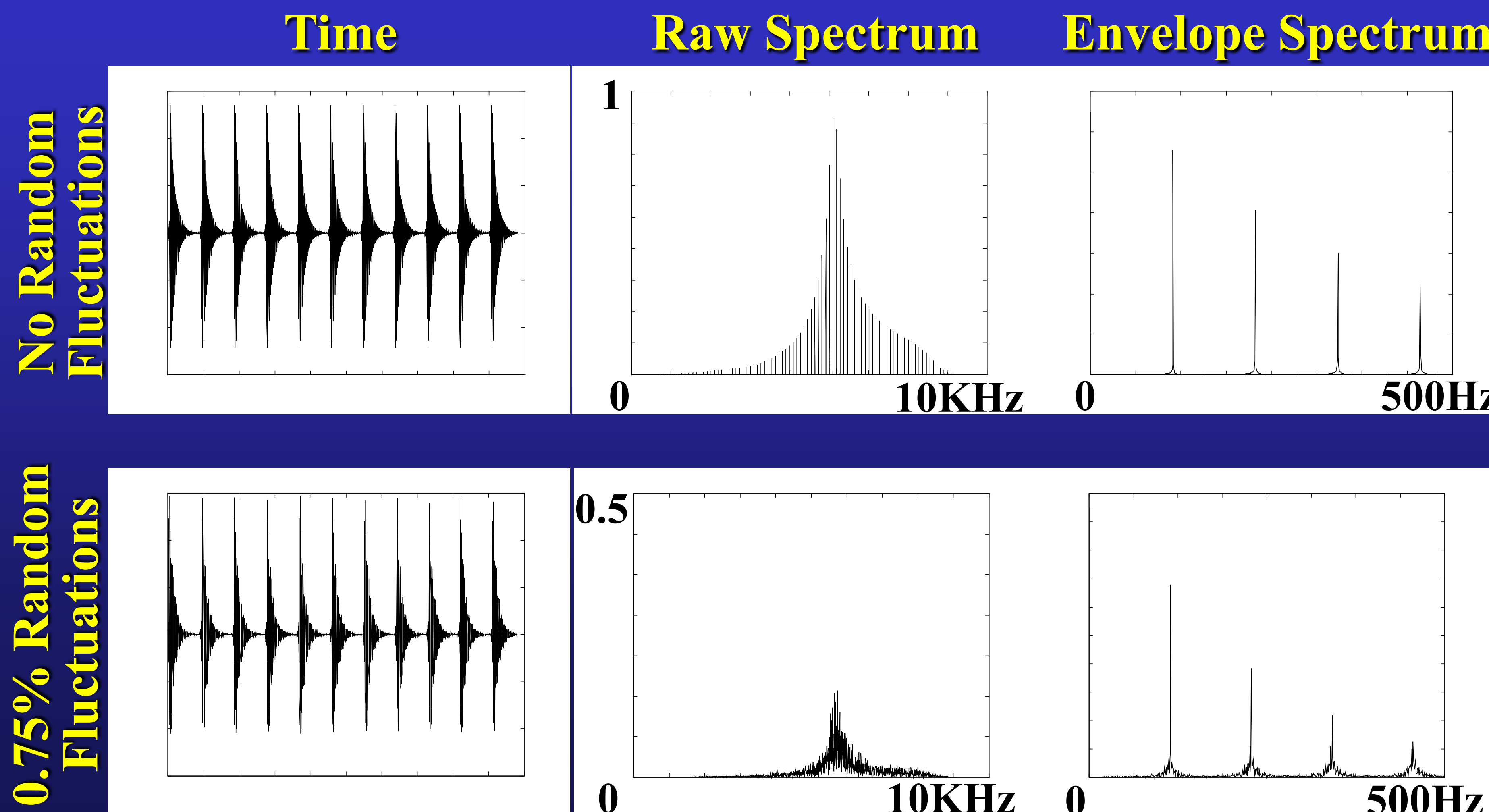
$$FTF = \frac{f_r}{2}\left\{1 - \frac{d}{D}\cos\phi\right\}$$ Cage

$$BSF = \frac{f_r D}{2d}\left\{1 - \left(\frac{d}{D}\cos\phi\right)^2\right\}$$ Rolling element

- The bearing fault “frequencies” are the kinematic frequencies assuming no slip
- Actual load angle ϕ varies with position of each rolling element in the bearing, giving different effective rolling diameter and slip
- This gives both a deviation and random variation of the order of 1-2 %, therefore not periodic but “cyclostationary”.

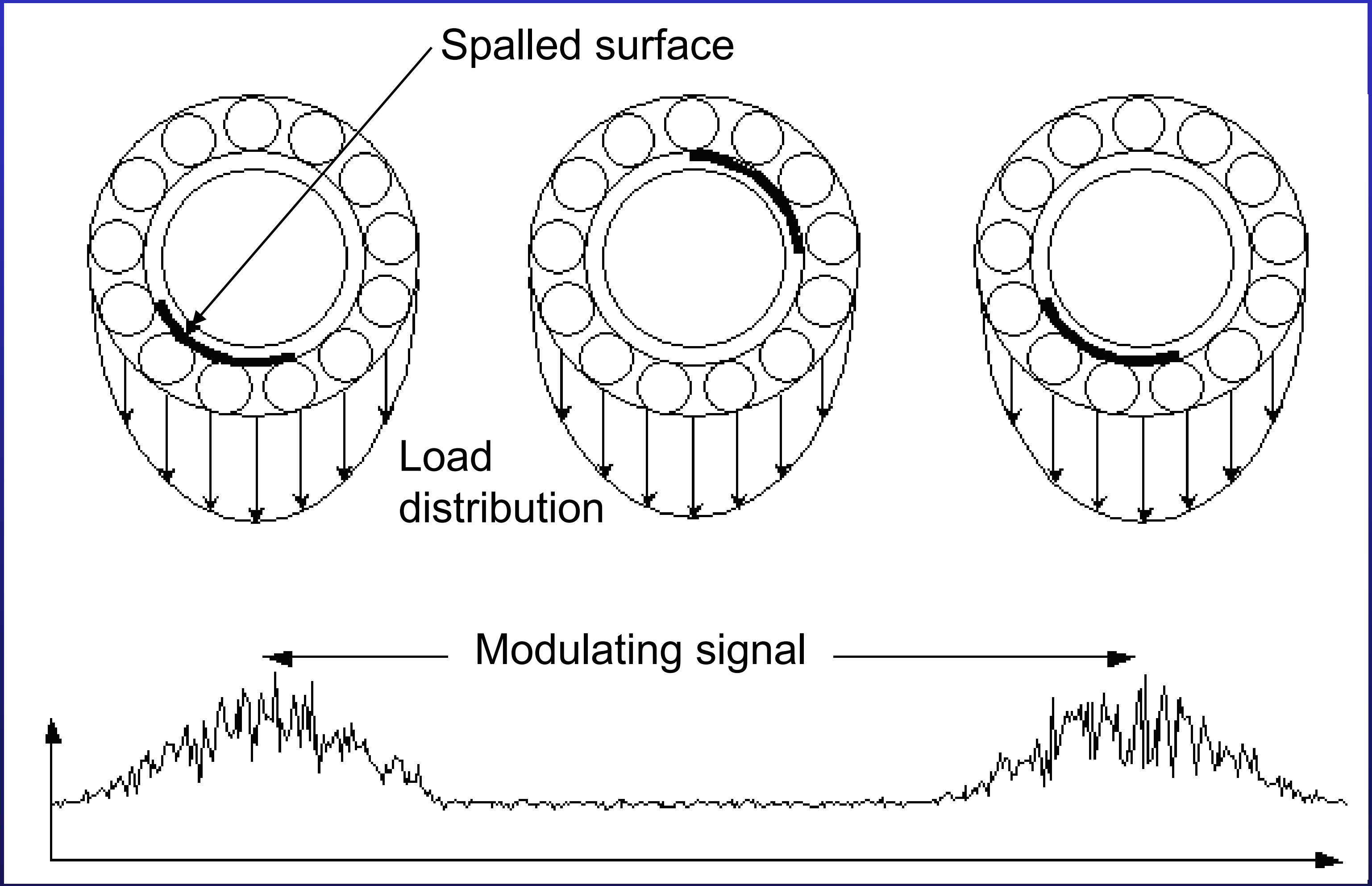
CONSEQUENCES OF SLIP

Information on periodicity removed from raw spectrum by a small amount of random fluctuation in pulse period. Periodicity still evident in envelope spectrum

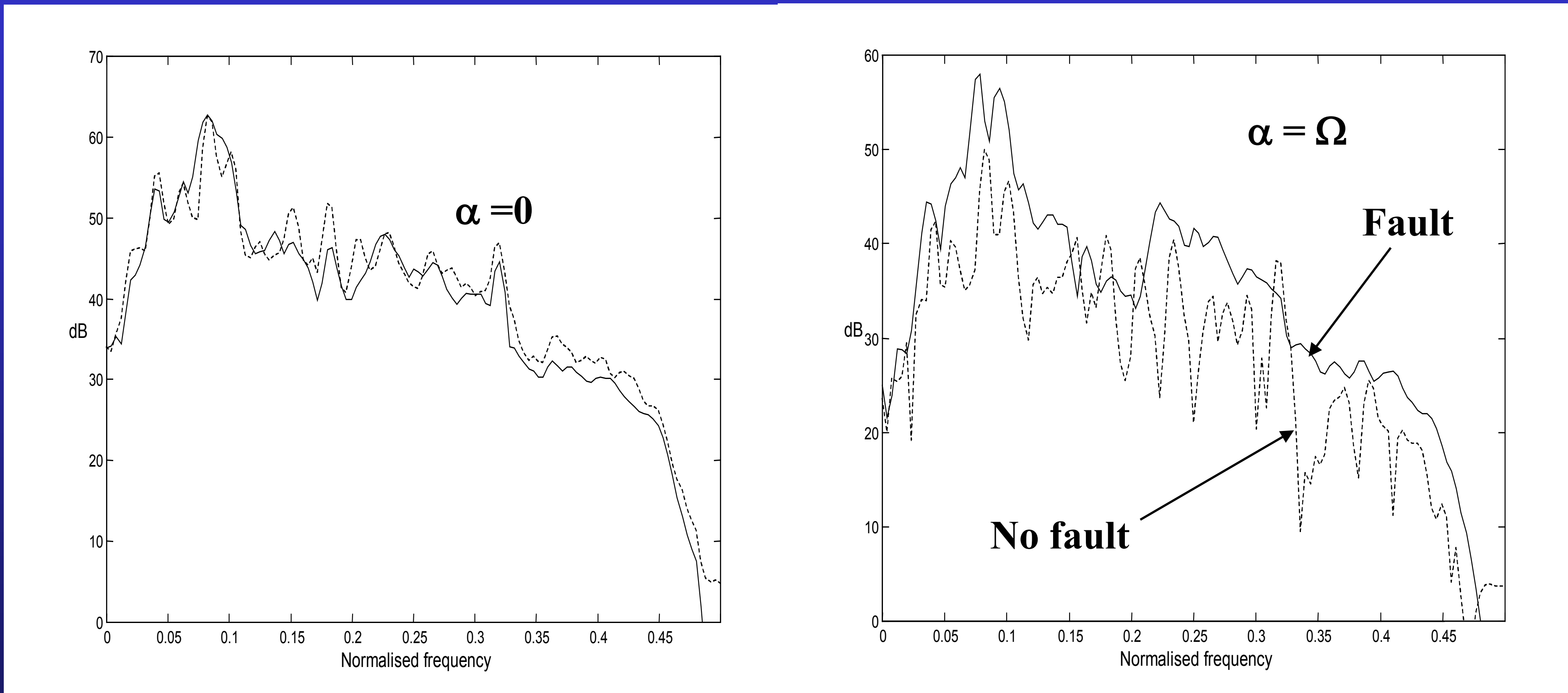


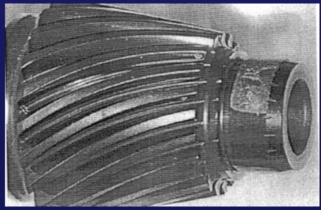
EXTENDED INNER RACE FAULT

Does not give high frequency bursts, but modulates gearmesh frequency



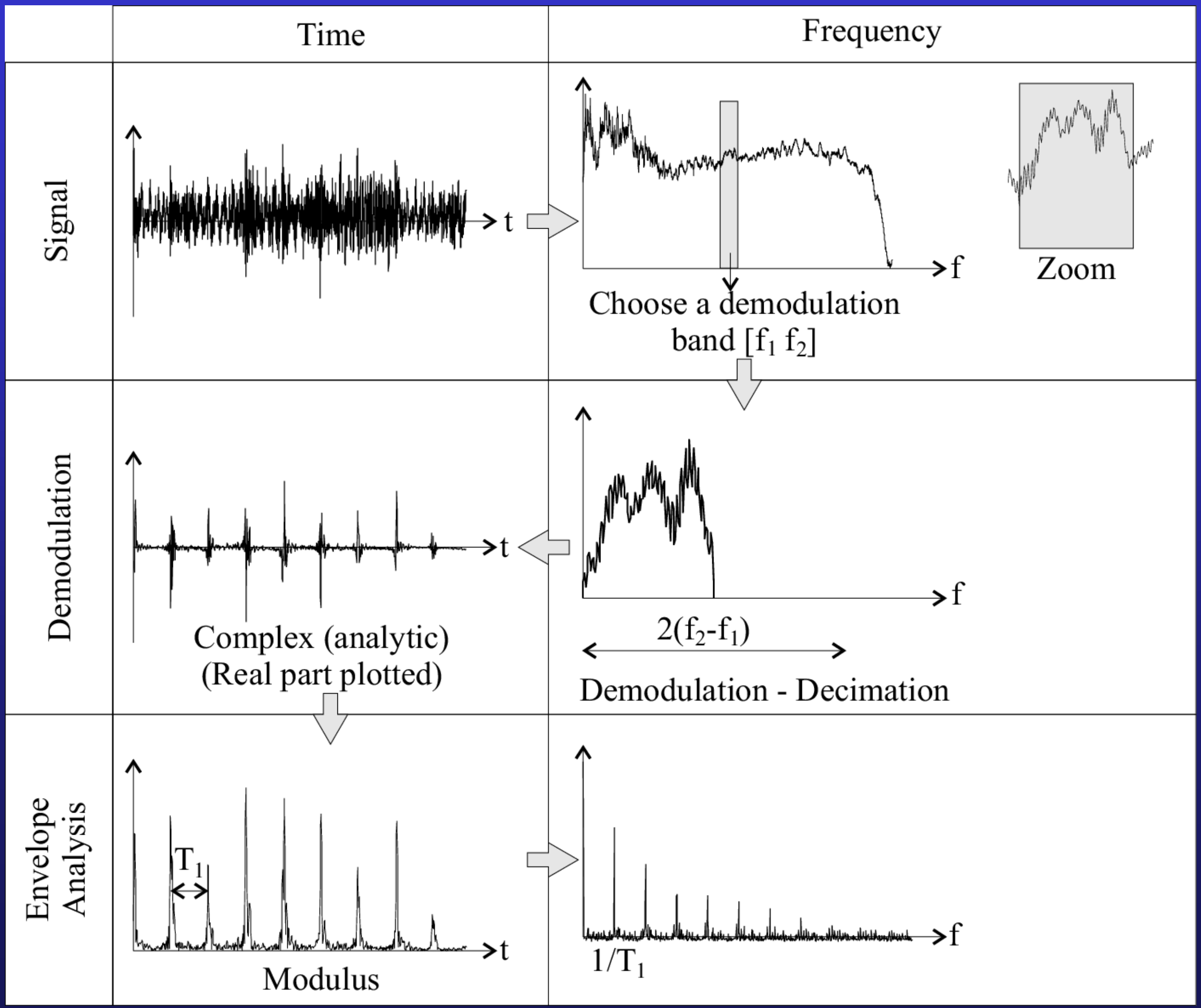
SOLUTION OF HELICOPTER INPUT PINION PROBLEM WITH EXTENDED INNER RACE FAULT





Distributed Inner Race Spall on Helicopter Input Pinion Bearing
(discrete frequencies removed using SANC)

HILBERT TECHNIQUE FOR ENVELOPE ANALYSIS



Bandpass filtration by an ideal filter

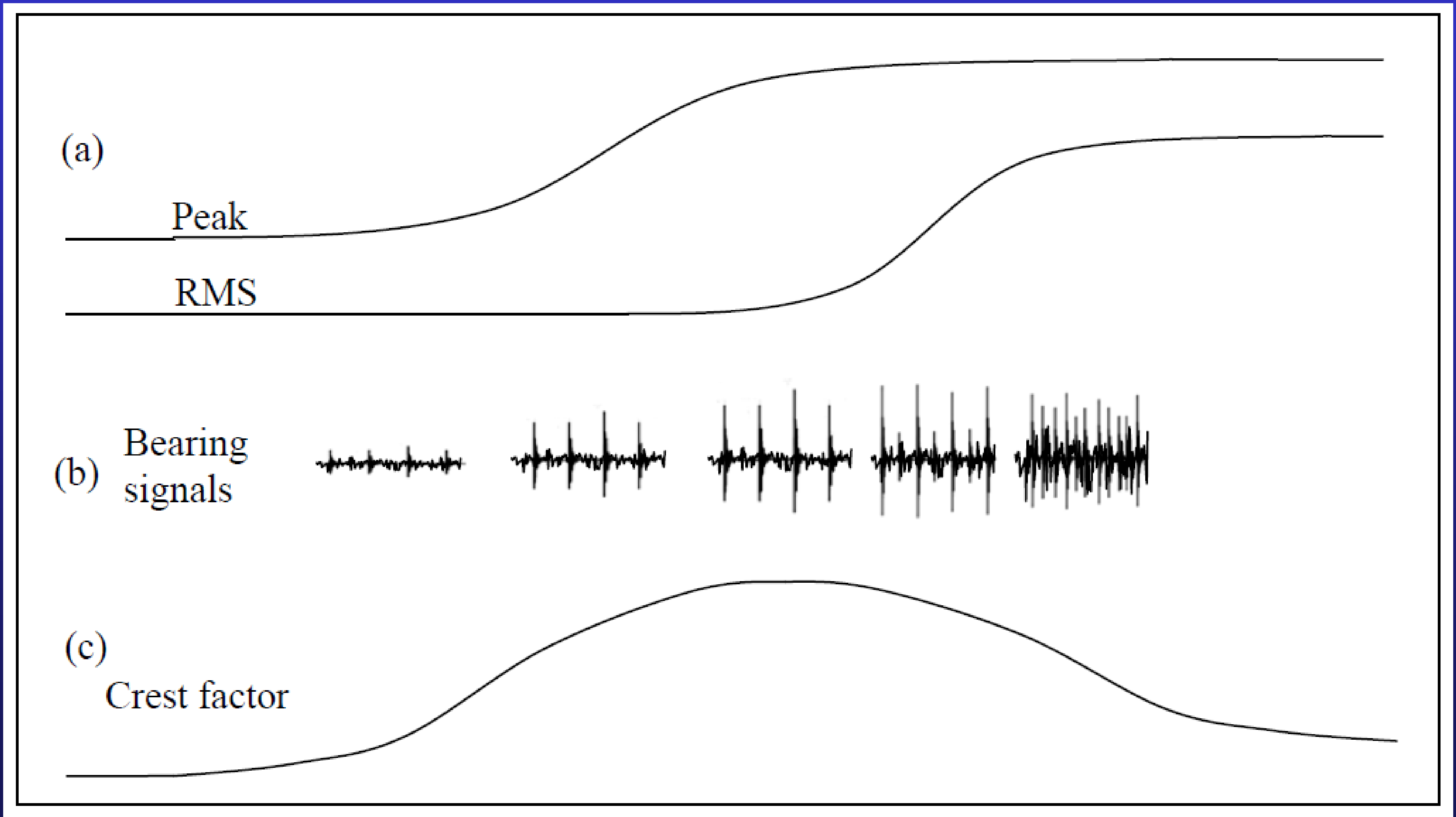
Reduction of sampling frequency

Envelope spectrum best from squared envelope

Problems with prognostics

- Incipient bearing faults often start with small spalls in the inner or outer race
- Spalls tend to have a constant depth (depth of maximum Hertzian shear stress), but initially the rolling element bridges over, so impacts increase with size until the rolling element "bottoms"
- Spalls extend in length but impacts at exit remain the same or decrease because of wear
- Cracks can be developing below the surface but do not show symptoms until "loss of metal"
- Multiple spalls develop, so RMS value increases while peak value stays the same or reduces. Crest factor and kurtosis first increase then reduce
- Envelope spectrum components can reduce as impulse responses bridge over

Typical development of crest factor (and kurtosis)



Some examples of trending bearing faults

1. Paper machine drive motor bearing

For simpler machines, RMS value in a frequency band often gives a good trend parameter

2. Auxiliary gearbox bearing on gas turbine driven oil pump

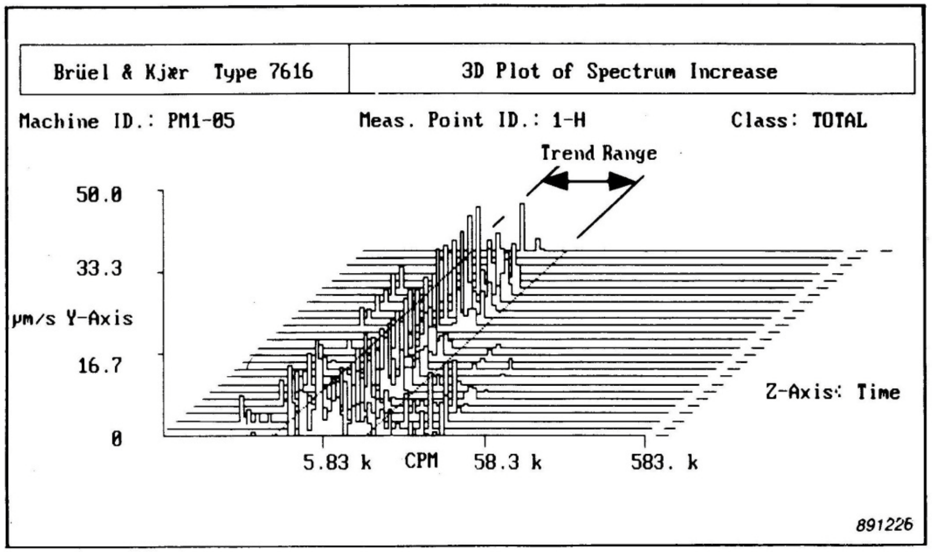
Summed harmonics of bearing frequency trended up then down (cepstrum useful to sum harmonics)

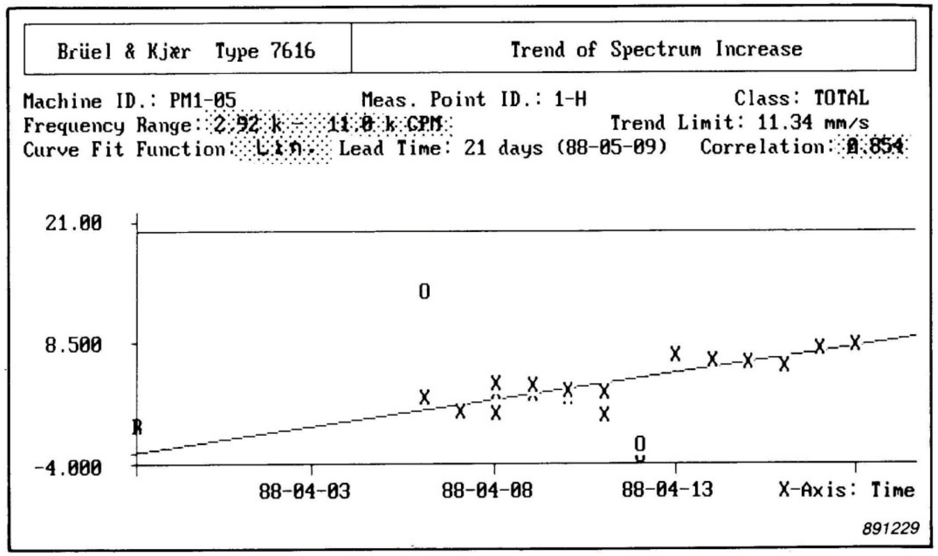
3. Helicopter gearbox planet bearing tested at full load on a test rig
4. High speed turbine bearing tested at full load on a test rig (two examples)

Two of these examples tend to indicate that spectral kurtosis (impulsiveness) tends monotonically to failure, but this is not typical, in particular for bearings not loaded permanently at full rated load

Motor bearing in a paper mill

Reported in B&K Application Note "Systematic Machine-Condition Monitoring - a Case Study from Parenco Paper Mill in Holland"

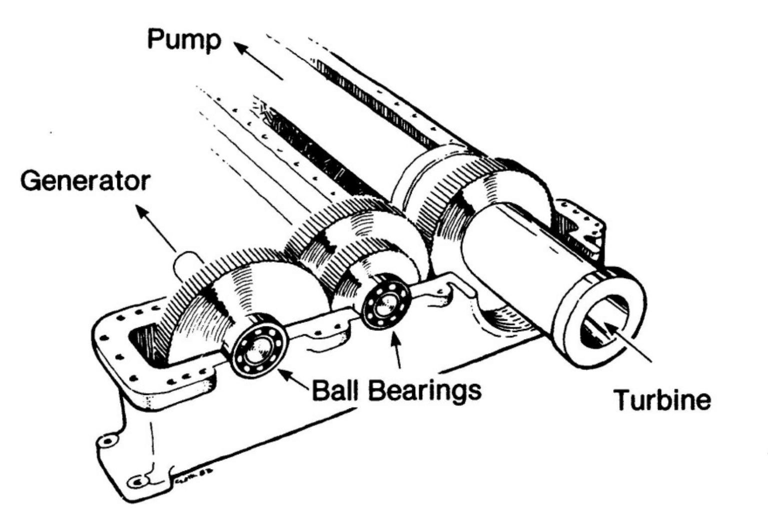




Trend band selected manually from 3D plot of spectrum differences

Trend curve has good correlation (0.854)

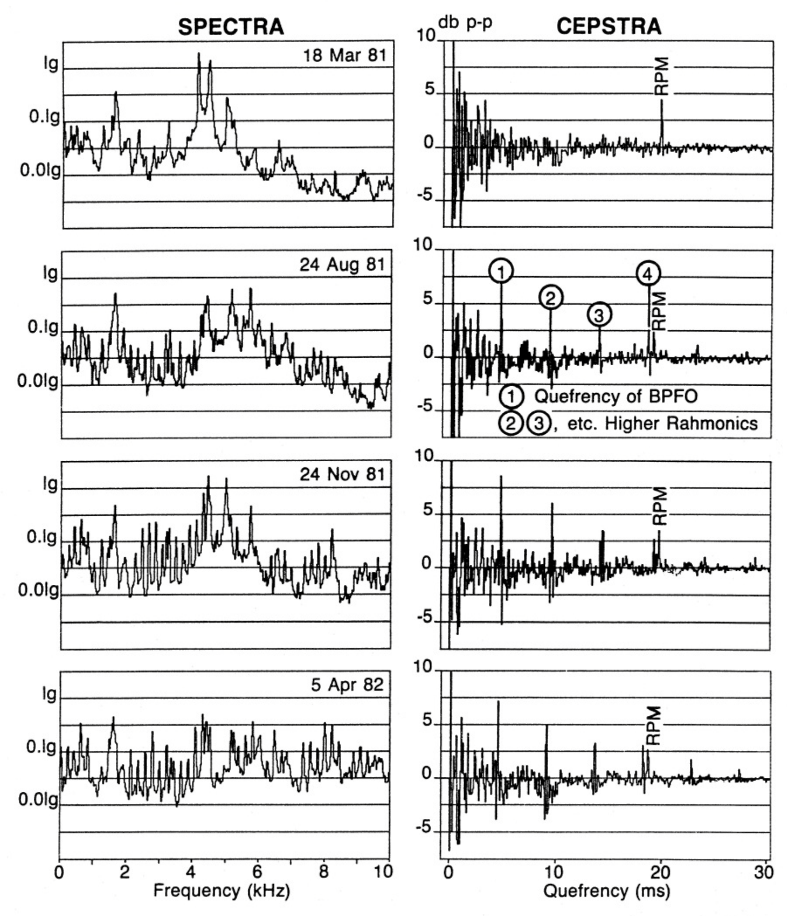
Auxiliary gearbox bearing on gas turbine driven oil pump (Trans Alaska Pipeline)



Example:
Auxiliary Generator Drive

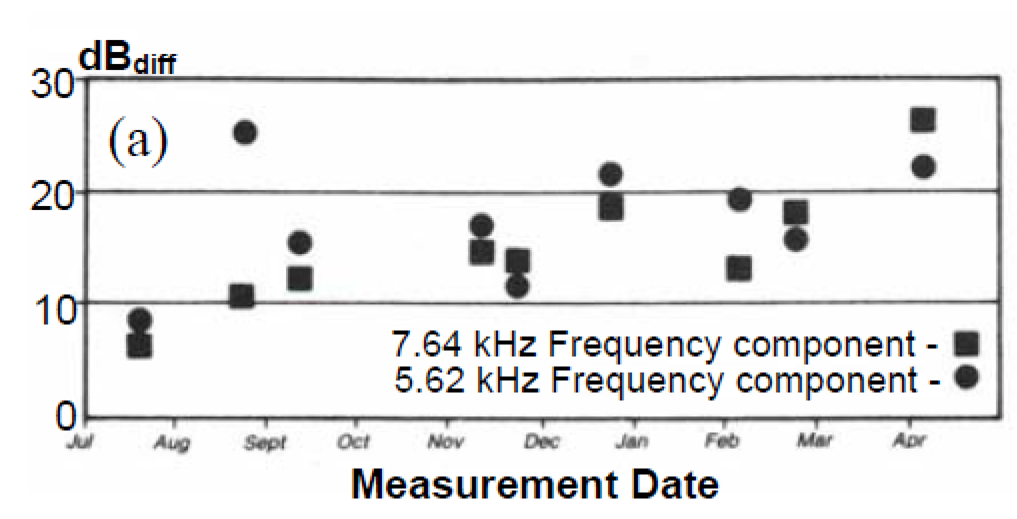
Power takeoff between turbine and oilpump on an Oil Pipeline
Problems arose in one of the bearings shown (and/or their counterparts at the other ends of the shafts)

Measurement point roughly in centre of upper casing (removed)

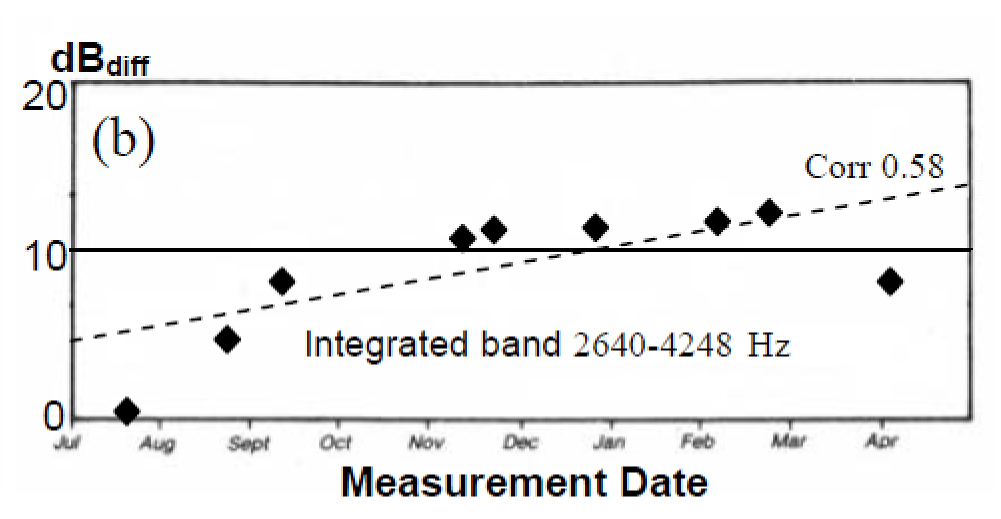


Trends in spectra and Cepstra

Trending of bearing harmonics

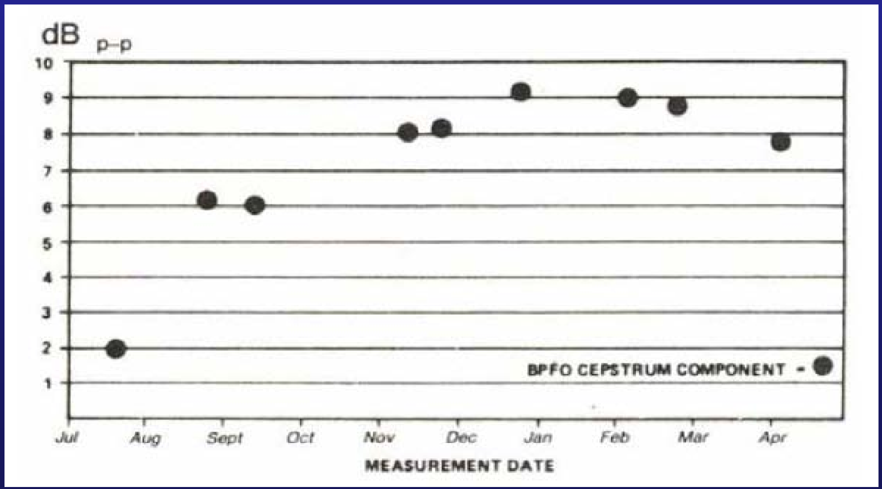


Individual harmonics vary widely



Integrated band gives smooth trend

Note that even when the trend is flat or downwards, subsurface cracking could be continuing



Cepstrum sums all harmonics with same spacing

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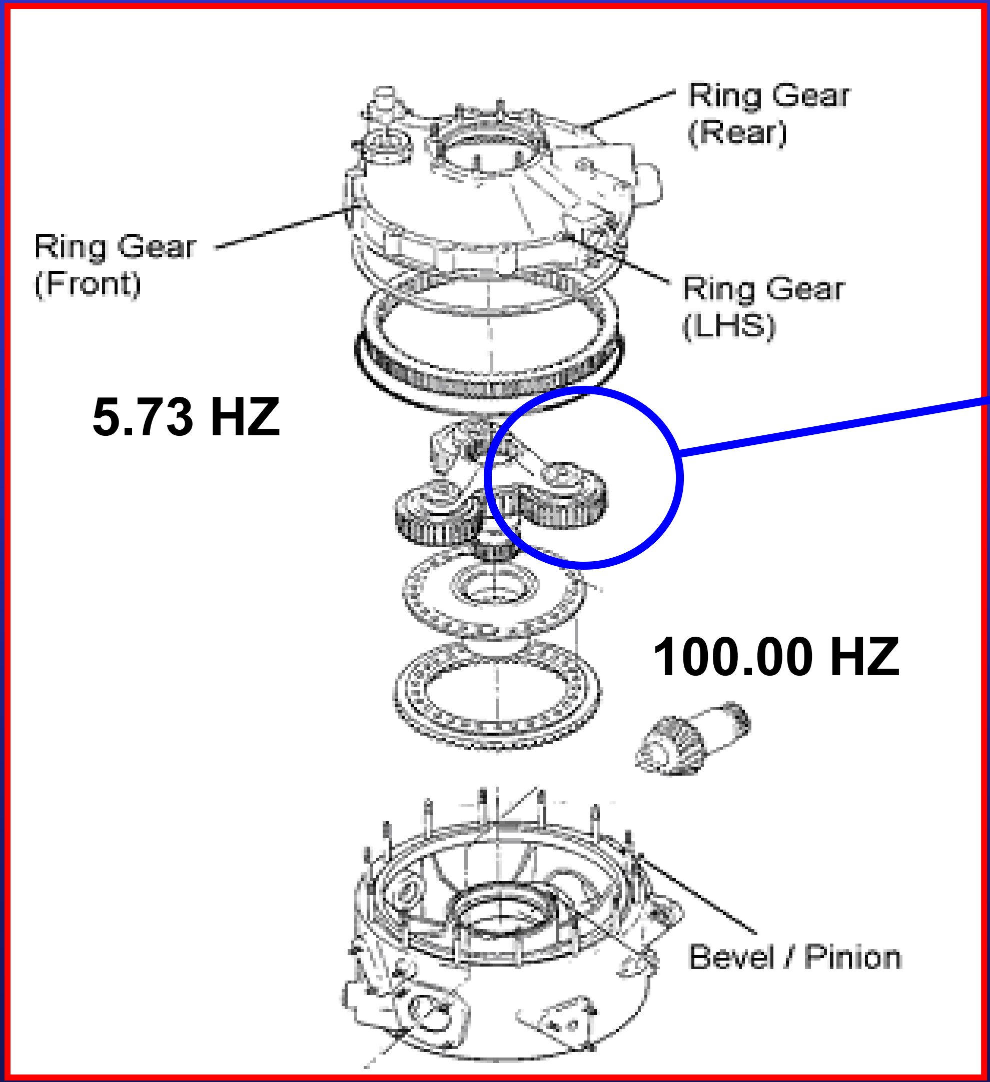
Case History – Helicopter Gearbox Rig



Blind analysis

Planetary Bearing

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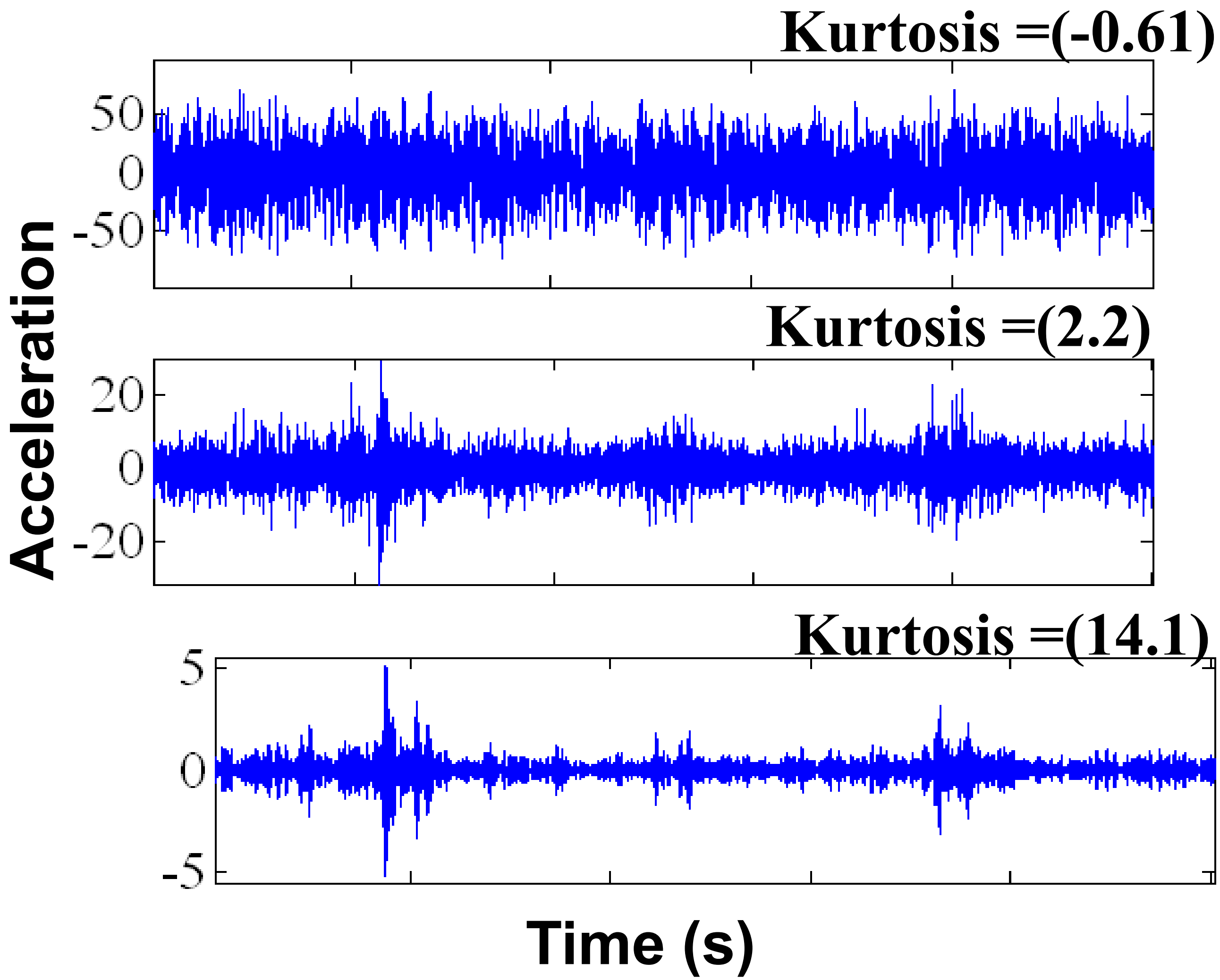
Time domain after filtration

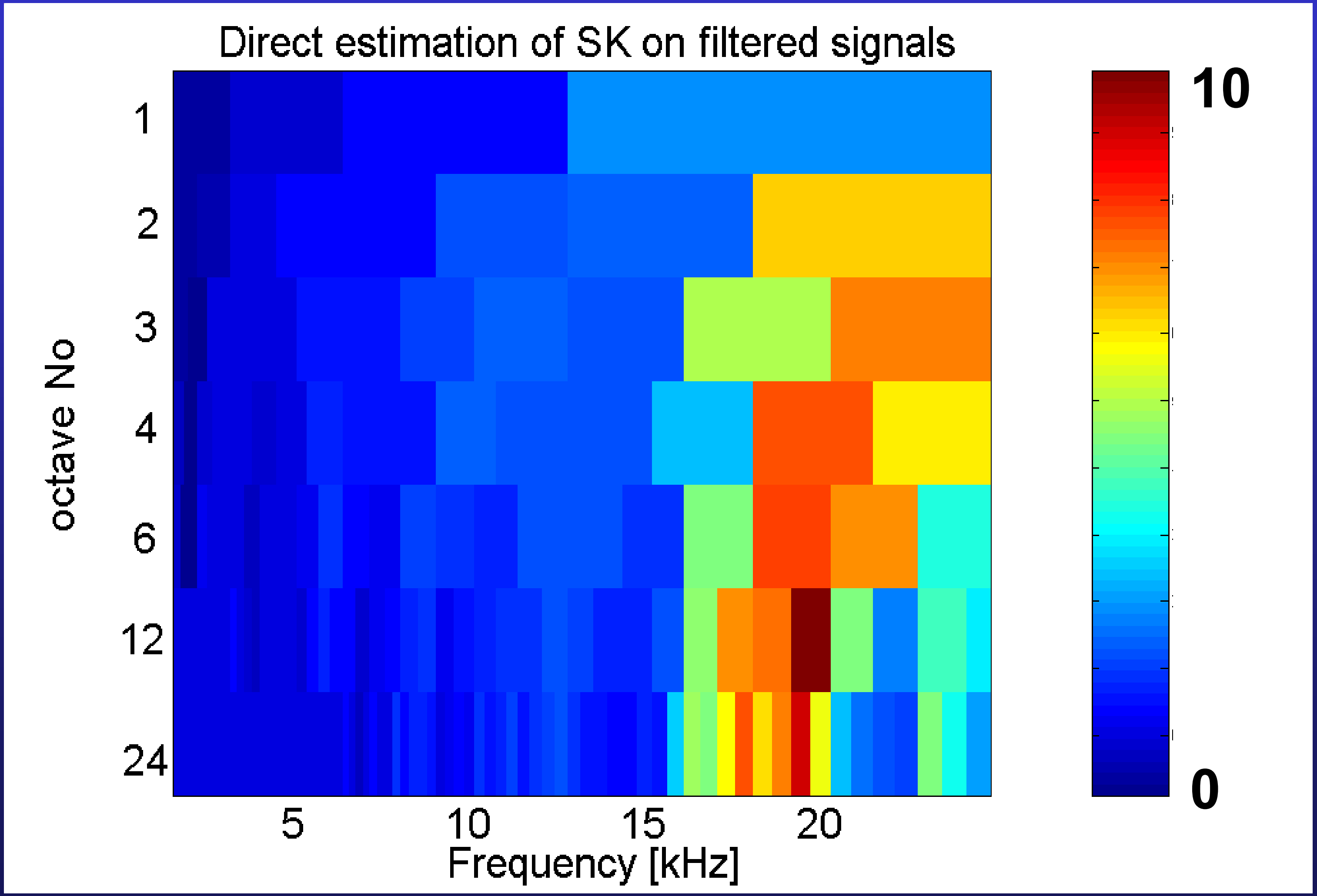
Order tracked signal

Residual signal after DRS and linear prediction

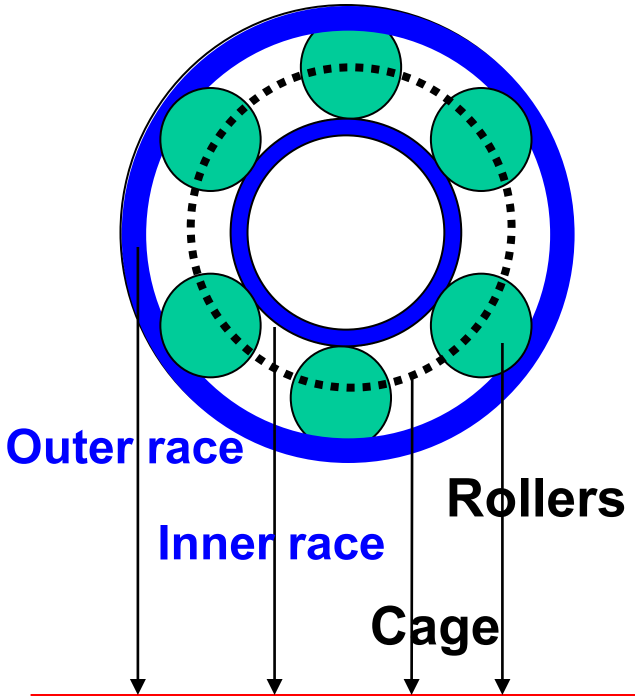
Filtered signal using SK



SK analysis showing the maximum excited bands

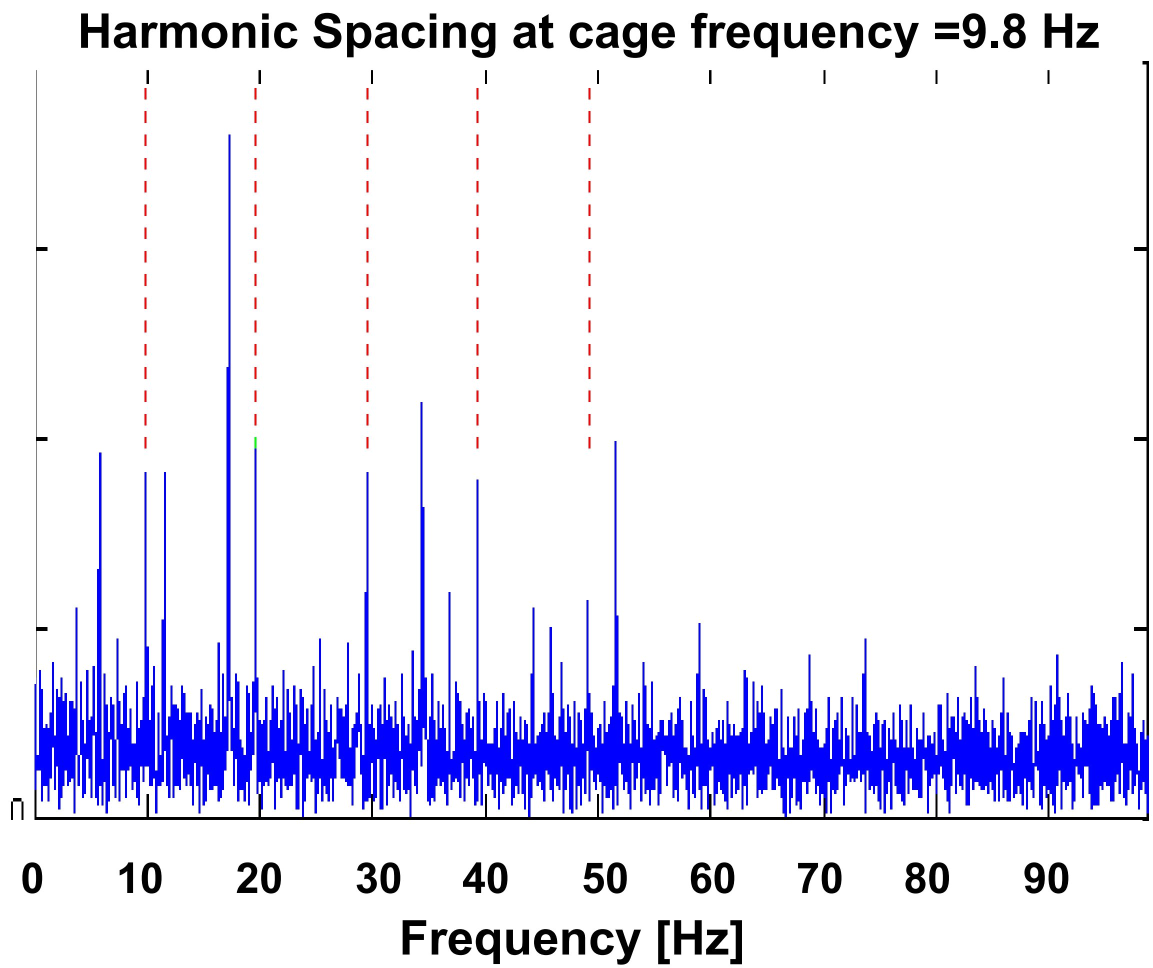


Squared Envelope Spectrum Showing Frequencies of Interest

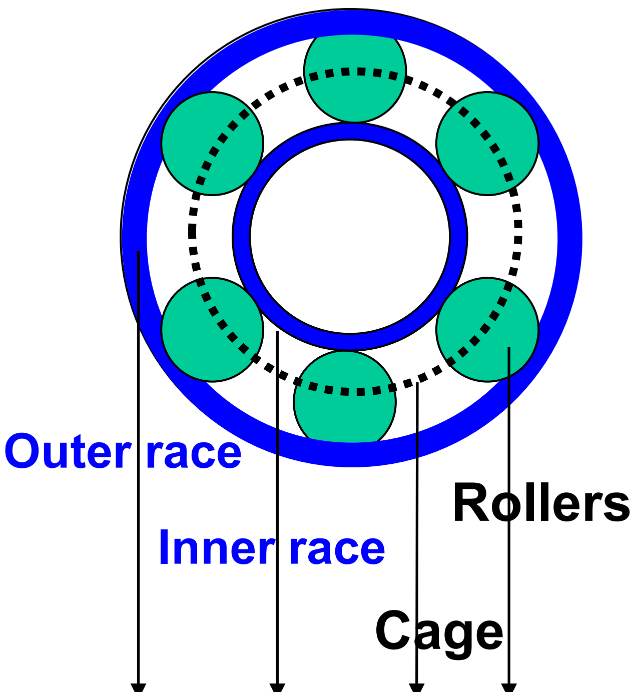


BPFO	BPFI	FTF	BSF
77.1	117.8	9.8	37.0

Planetary Bearing Defect Frequencies



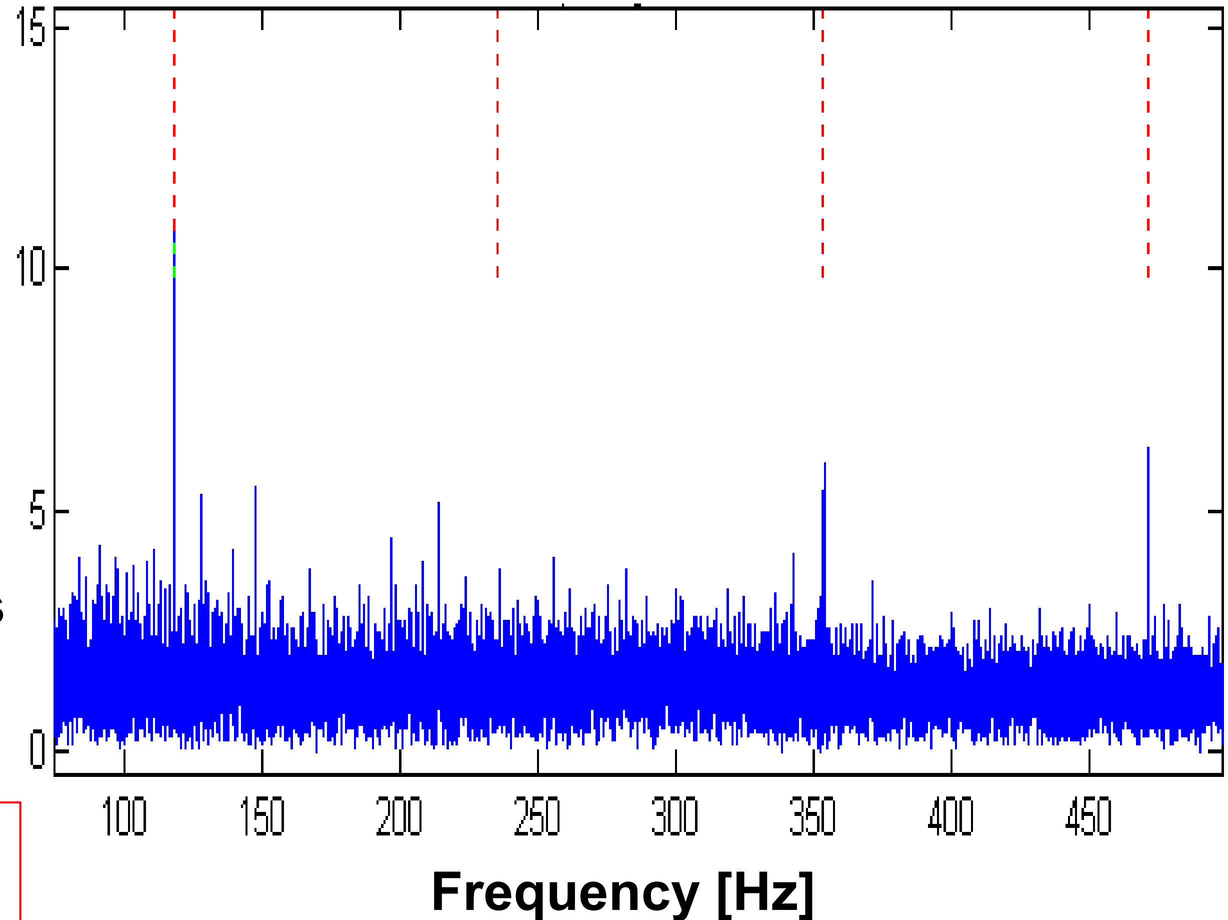
Squared Envelope Spectrum Showing Frequencies of Interest



BPFO	BPFI	FTF	BSF
77.1	117.8	9.8	37.0

Planetary Bearing Defect Frequencies

Harmonic Spacing at BPFI =117.7 Hz



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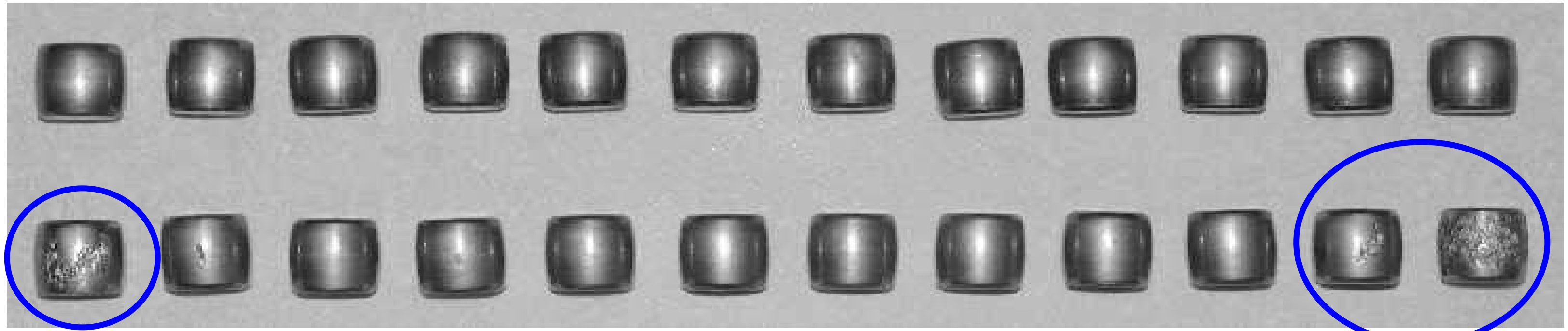
Findings Agree With Analysis Results

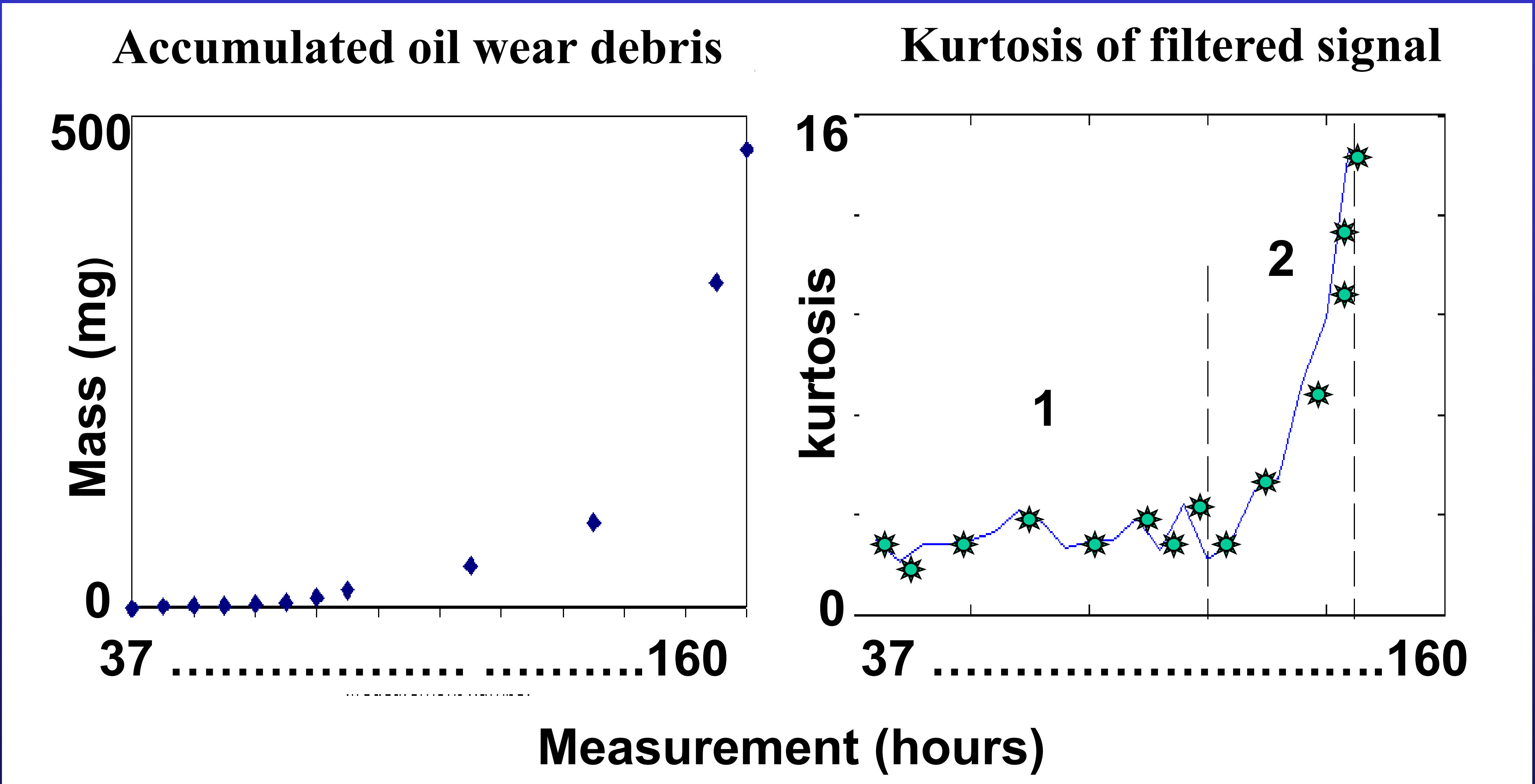
Planetary Bearing

Inner Race



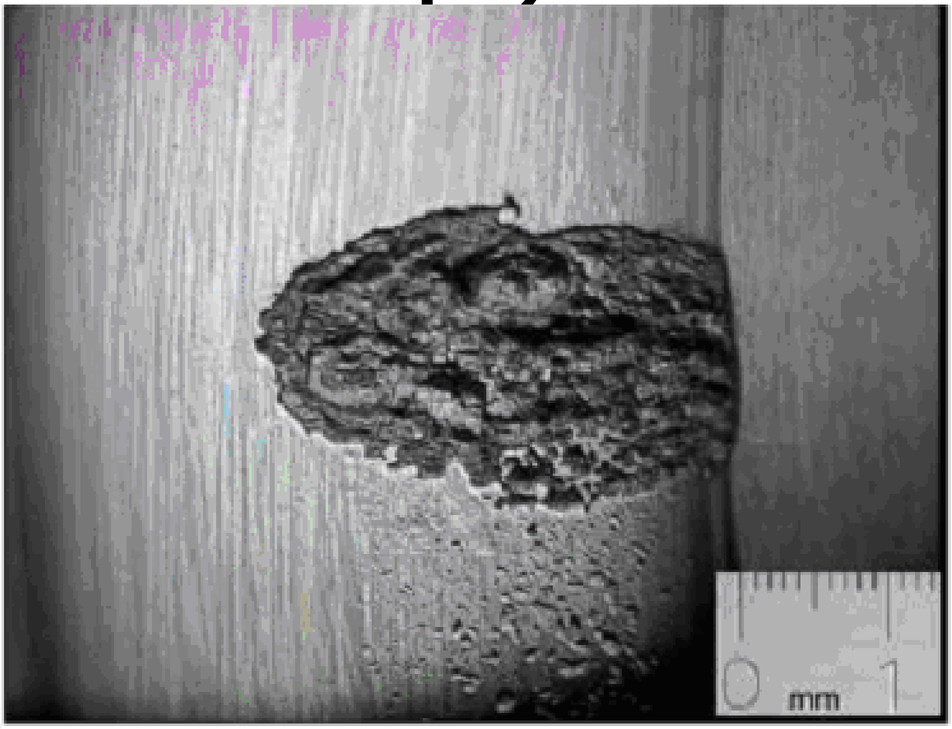
Rollers

Trending based on SK vs. Oil Wear Debris



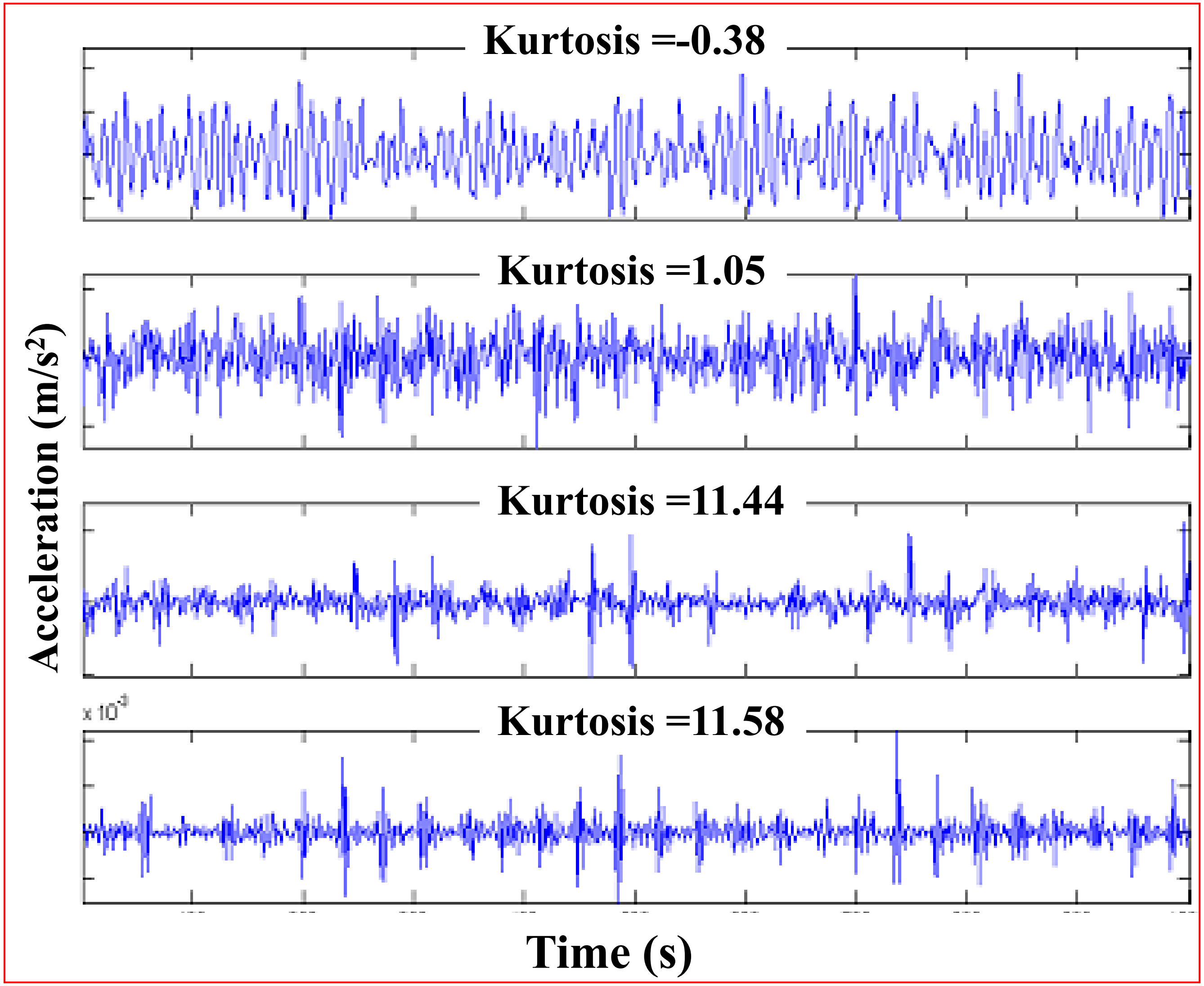
Second Case History
High Speed Bearing Test Rig

FAG Test Rig L17 .. High Speed (12,000 rpm)



Spall in the inner race

The Effect of using the MED Technique



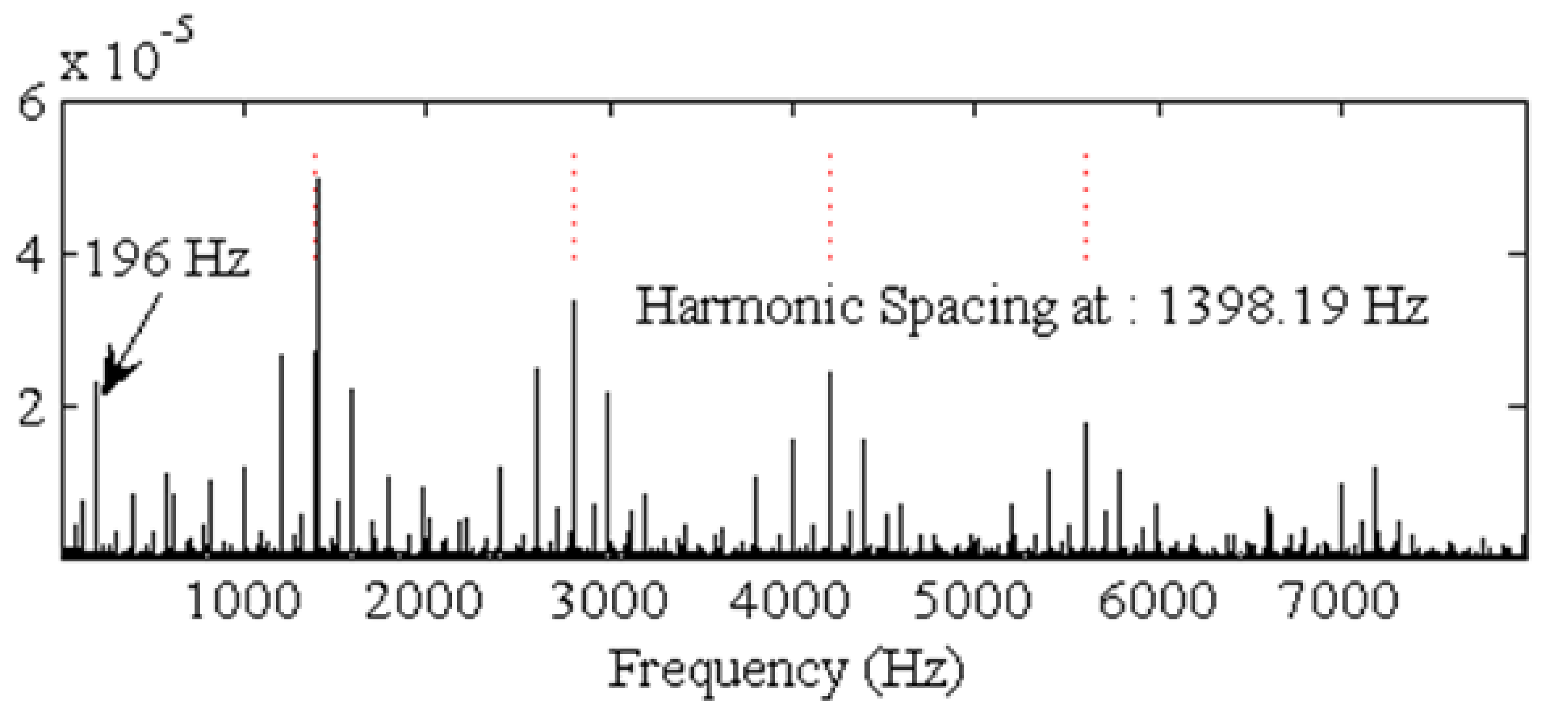
(a) Raw signal

(b) Residual of linear prediction filtering

(c) Signal b filtered using MED

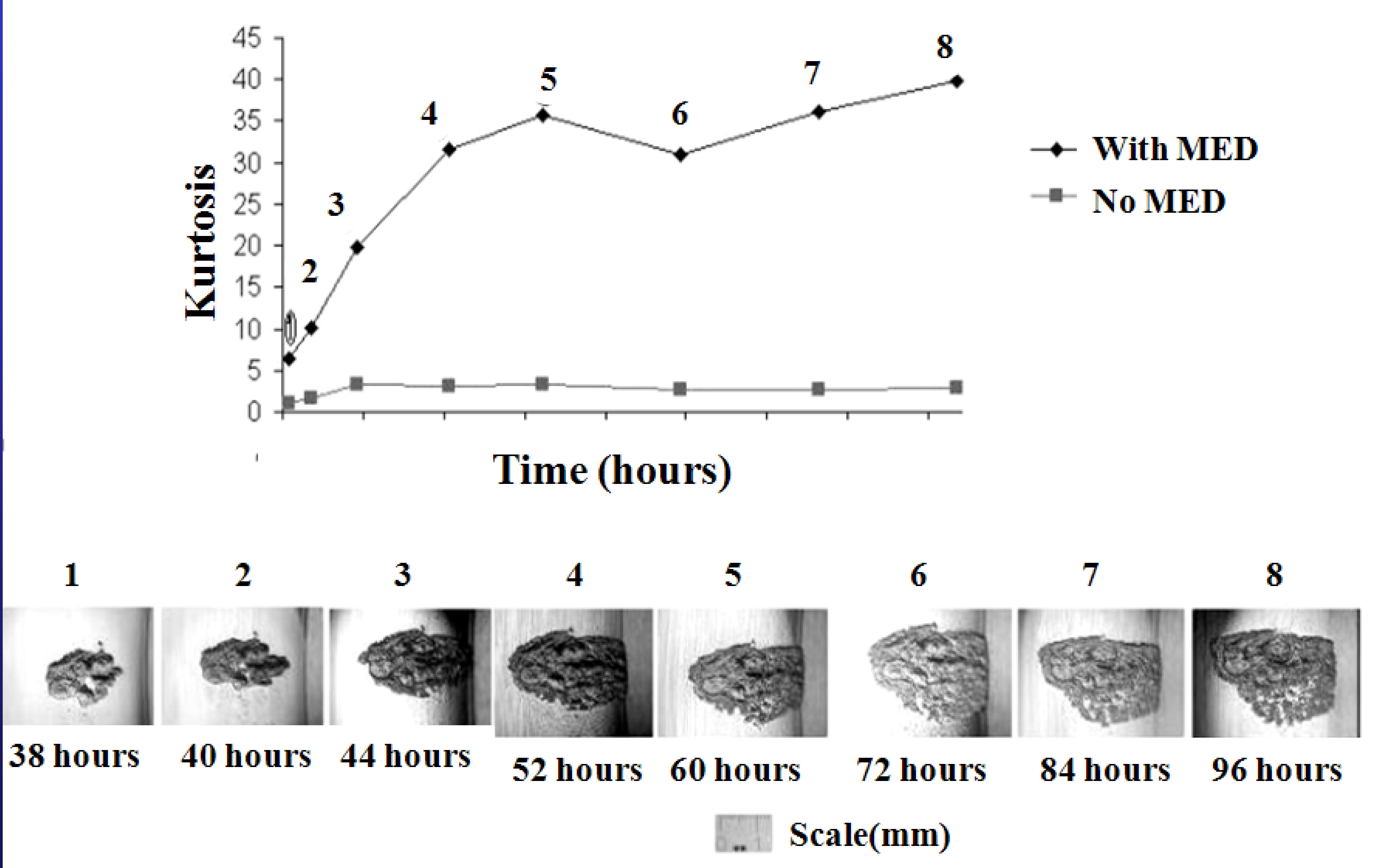
(d) Signal c filtered using optimal SK filter

Envelope Analysis after MED and SK

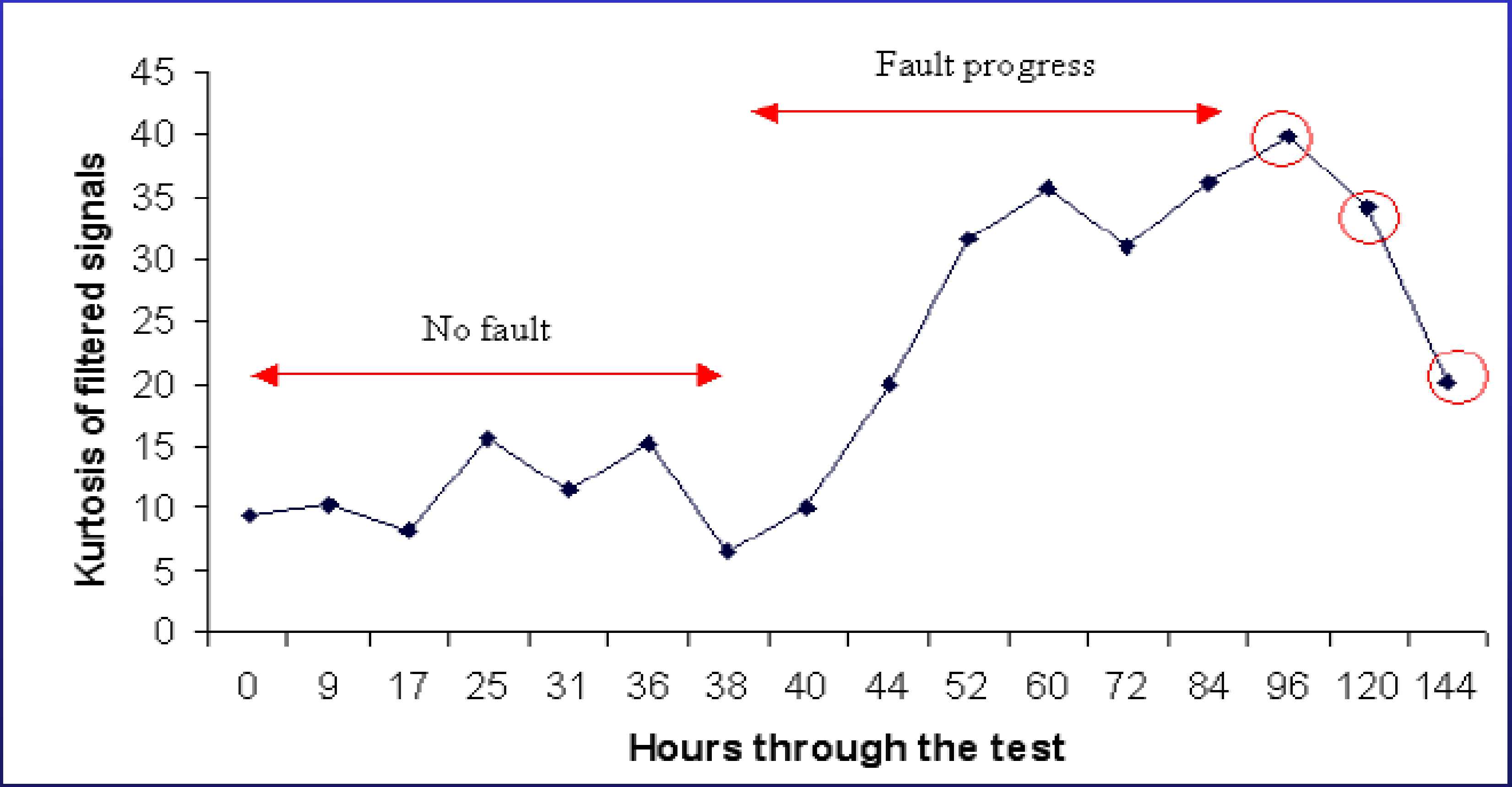


Harmonics at BPFI, sidebands at shaft speed

Trending Fault Development



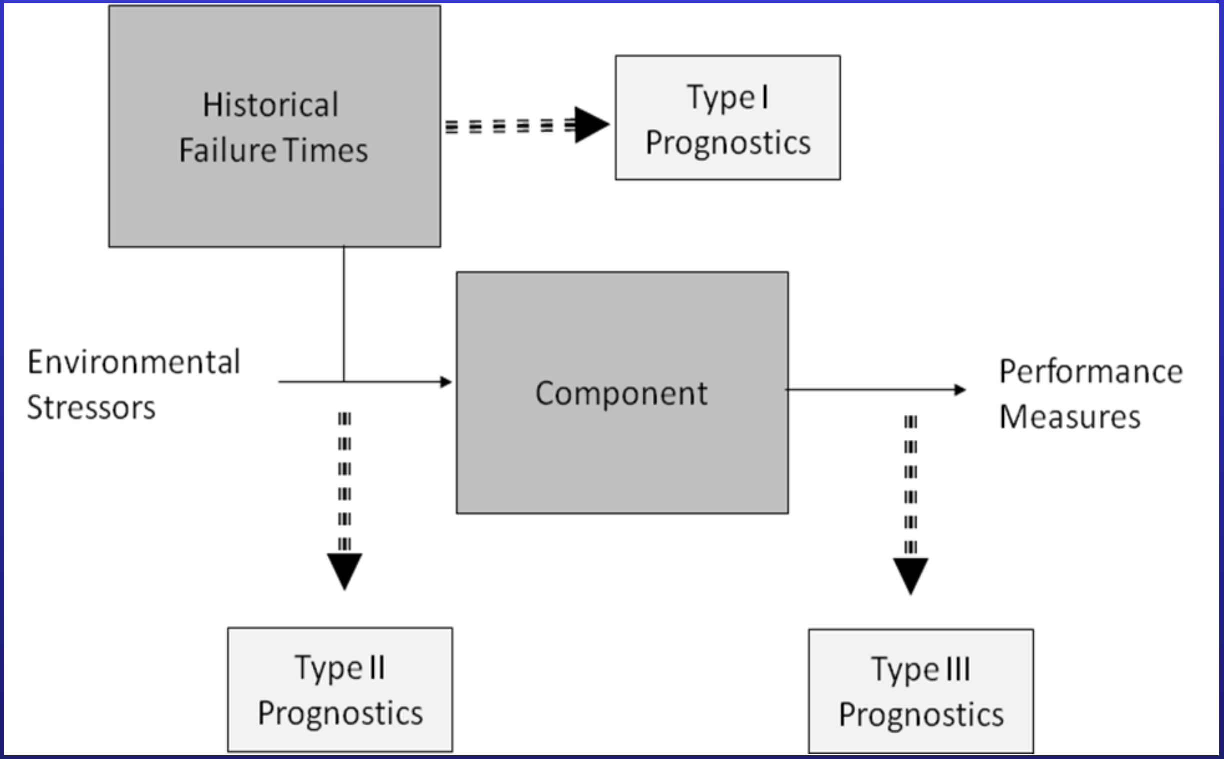
Trend for another bearing on the high speed test rig



Indicates that even when the load is continuously high the trend is not necessarily monotonic

Advanced Prognostics

J. W. Hines and A. Usynin (2008) "Current Computational Trends in Equipment Prognostics", *Int. J. of Computational Intelligence Systems*, 1(1), pp. 95-109.



Type 1: Reliability based – same for whole population

Type 2: Account for Environmental Stressors – same for whole machine

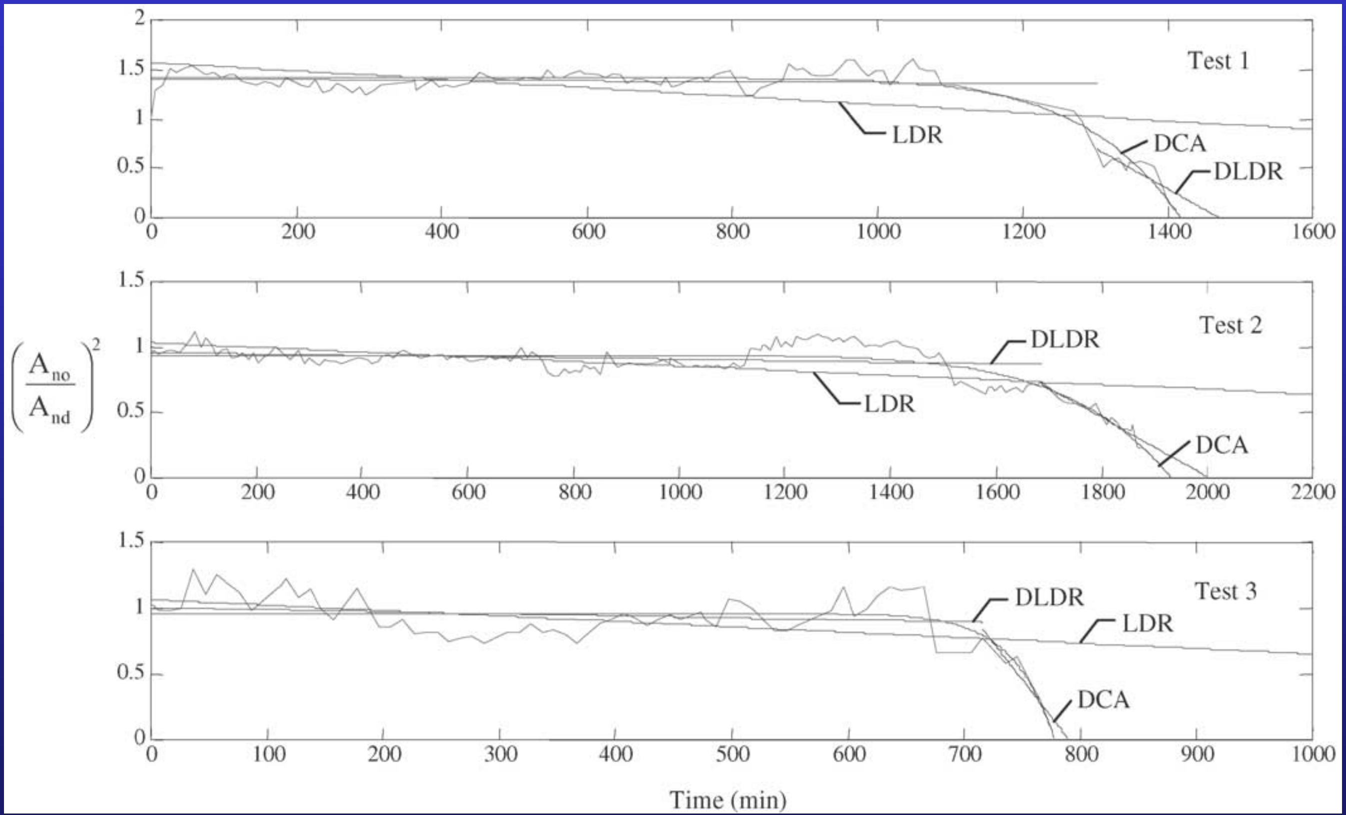
Type 3: Measures of current state – separate for each component

Proposals for Bearing Prognostics

Based on vibration measurements

- **Models based on Paris law** “Paris, P.C and Ergodon, F. (1963): A pitting model for rolling contact fatigue *ASME Transactions, Journal of Basic Engineering*, vol.85, pp. 528-534”
  eg Li, Y., et al (2000): Stochastic prognostics for rolling element bearings. *Mechanical Systems and Signal Processing,* vol. 114(5), pp. 747-762**.**
  Assumes fault area is linearly related to RMS vibration level
- **Spall progression models, eg** “Kotsalas & Harris (2001) Fatigue Failure progression in Ball Bearings, Trans ASME, Vol. 123, pp.238-242.
  Applied in fusion with oil wear debris data in “M.J. Roemer, et al (2005) Prognosis of Rotating Machinery Components. Chapter 19 in *Damage Prognosis for Aerospace, Civil and Mechanical Systems*, Wiley.
- **Detection of a change in “bearing natural frequency”** Qiu et al “Damage Mechanics Approach for Bearing Lifetime Prognostics” MSSP (2002) 16(5), 817–829
- **Co-variate analysis used to train ANN.** A. Heng et al (2009), Intelligent condition-based prediction of machinery reliability *Mechanical Systems and Signal Processing*, 23(5), pp. 1600-1614.
  Requires data from actual failures

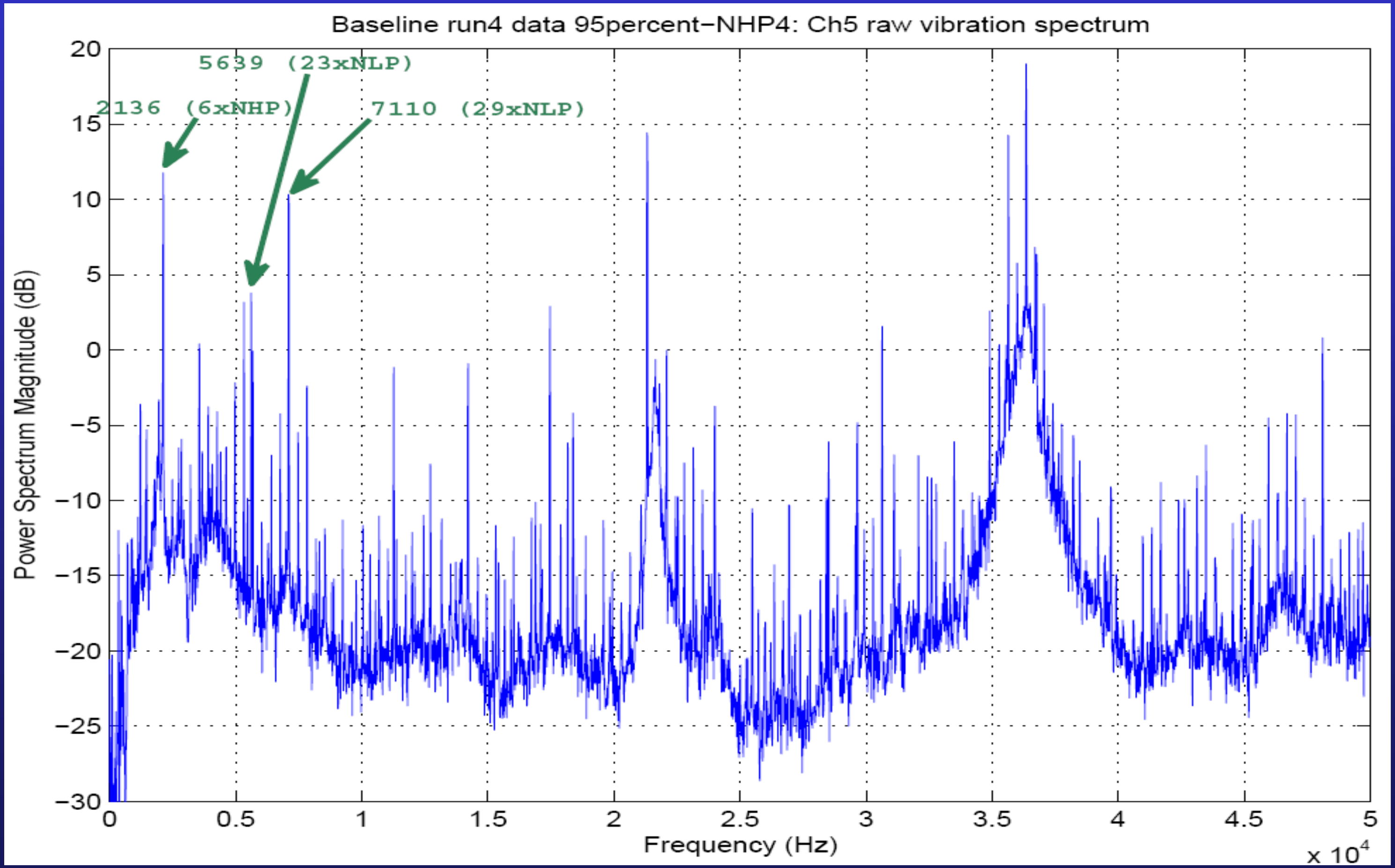
Qiu et al "Damage Mechanics Approach for Bearing Lifetime Prognostics"



The paper does not explain how the information on "bearing natural frequency" was extracted from the measurements, and shows no spectra

Typical gas turbine spectrum

What's the natural frequency of the third bearing from the left?



Wang ISABE-2009-1127 Turbine engine bearing fault diagnosis

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Bearing Fault Development

Wenyi Wang (DSTO), Comadem conference, Stavanger 2011

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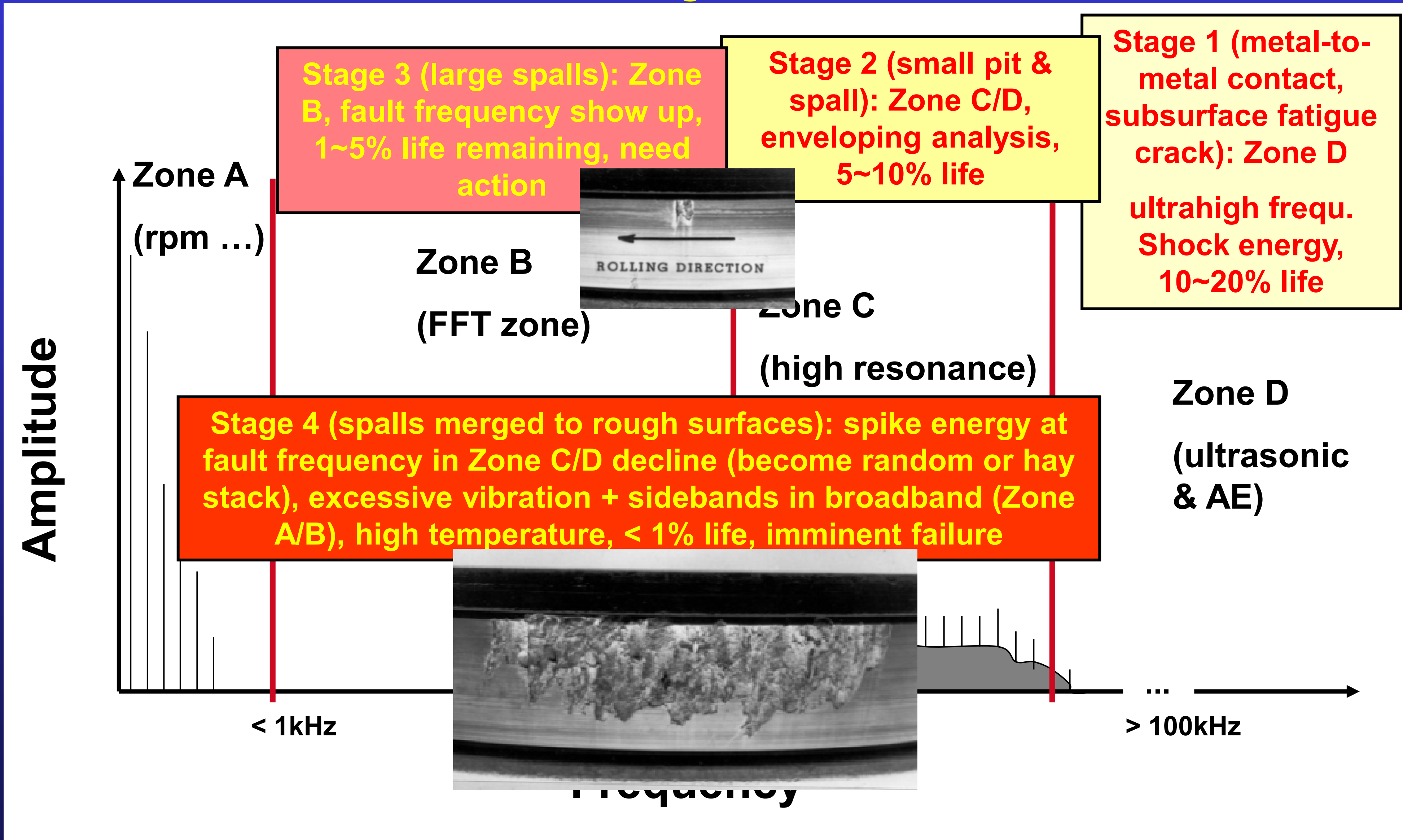

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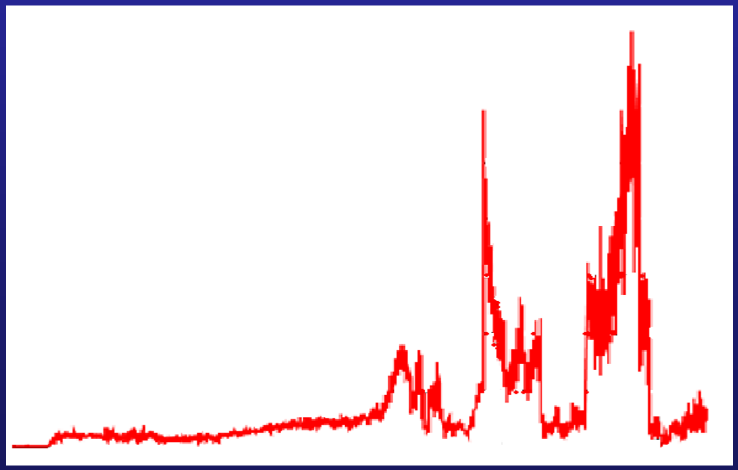
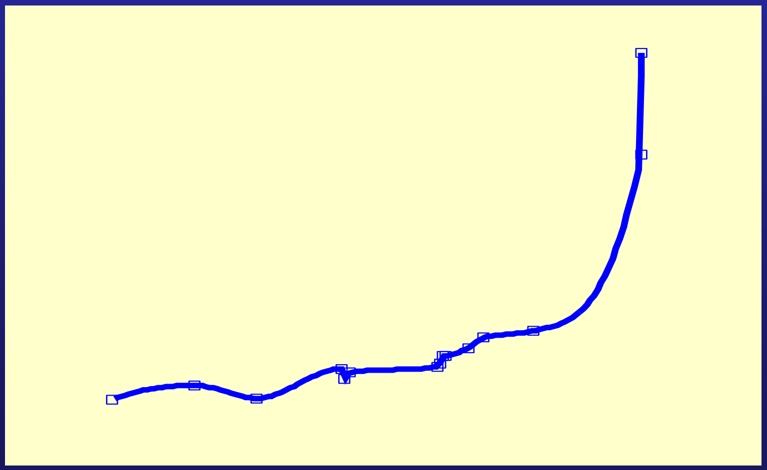
Wenyi Wang
Proposal for bearing fault trending
Comadem conference, Stavanger 2011

- First remove all synchronous and bladepass components from signal to leave the bearing signal
- Because the frequency content changes from high to low over the life of the bearing, take the total RMS value over the whole frequency range as a trend parameter. More likely monotonic.



High frequency band

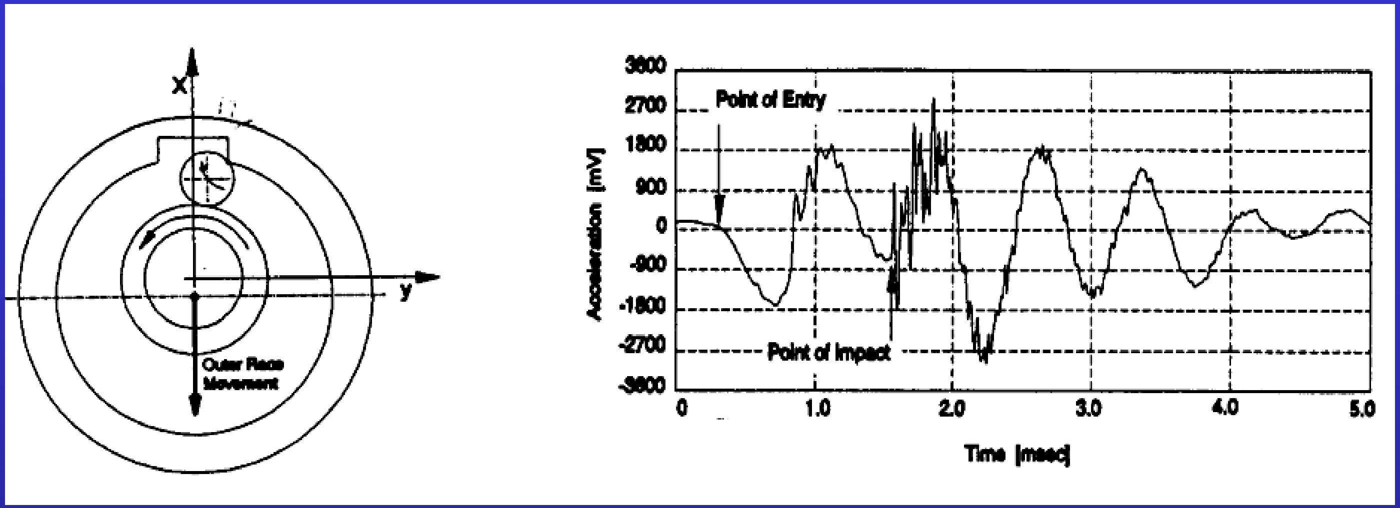


Full frequency band

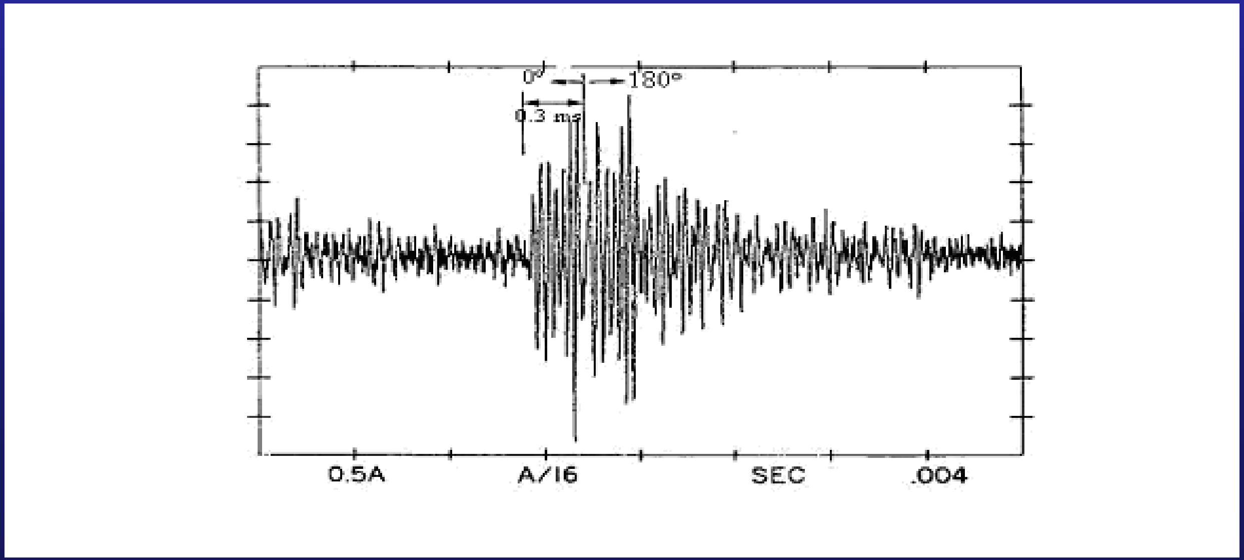
Determination of spall size

- Bearing prognostics an important economic factor – major benefit in predicting remaining useful life
- Measuring size of a spall would give valuable feedback to prognostic algorithms
- Few papers showing signals at entry to and exit from a spall
- Entry is a step response (step change in acceleration) by sudden change in curvature of path
- Exit is an impulse response corresponding to a step response in velocity (change in direction)

Previous publications

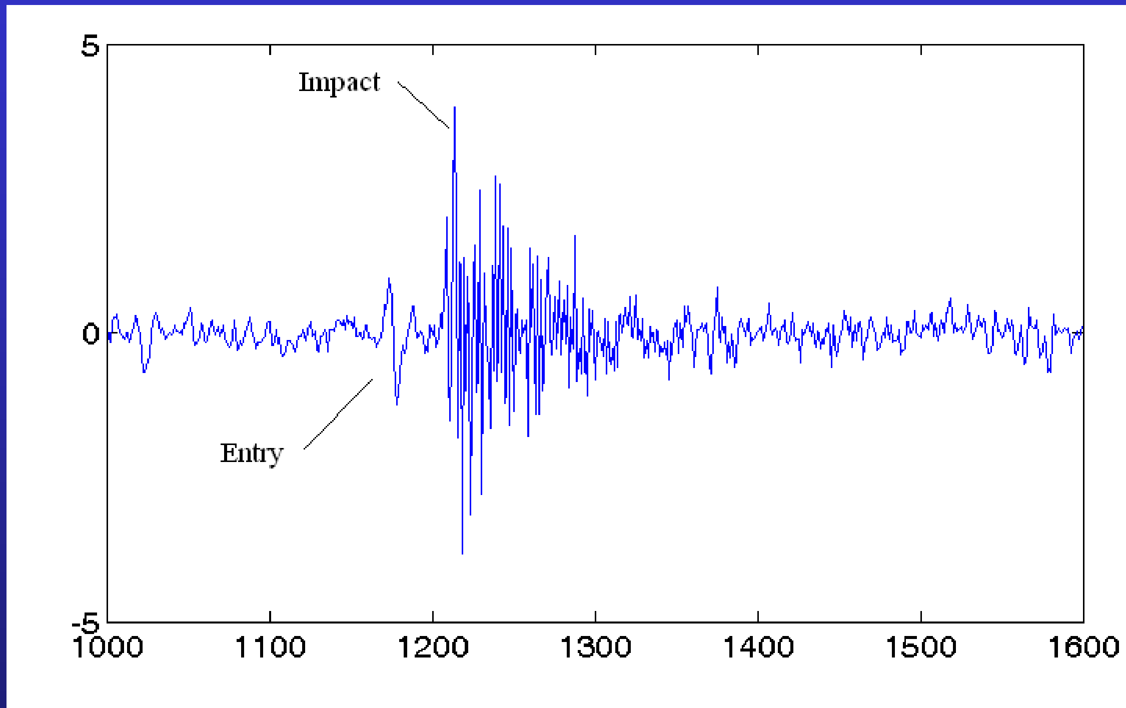


Epps & McCallion (1994)



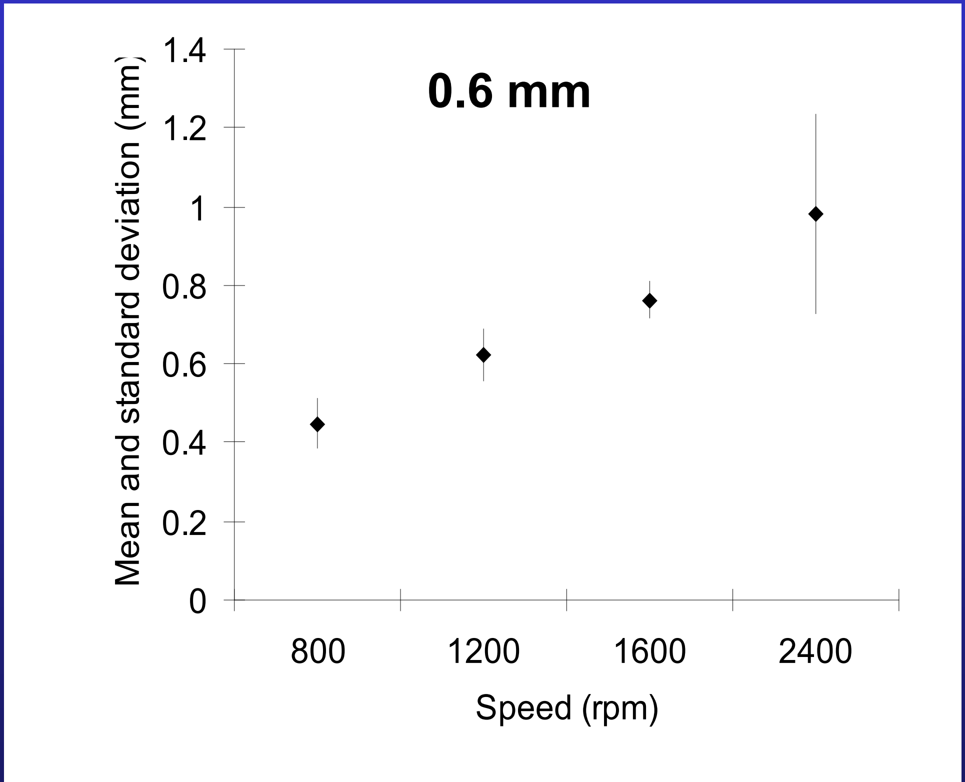
Dowling (1993)

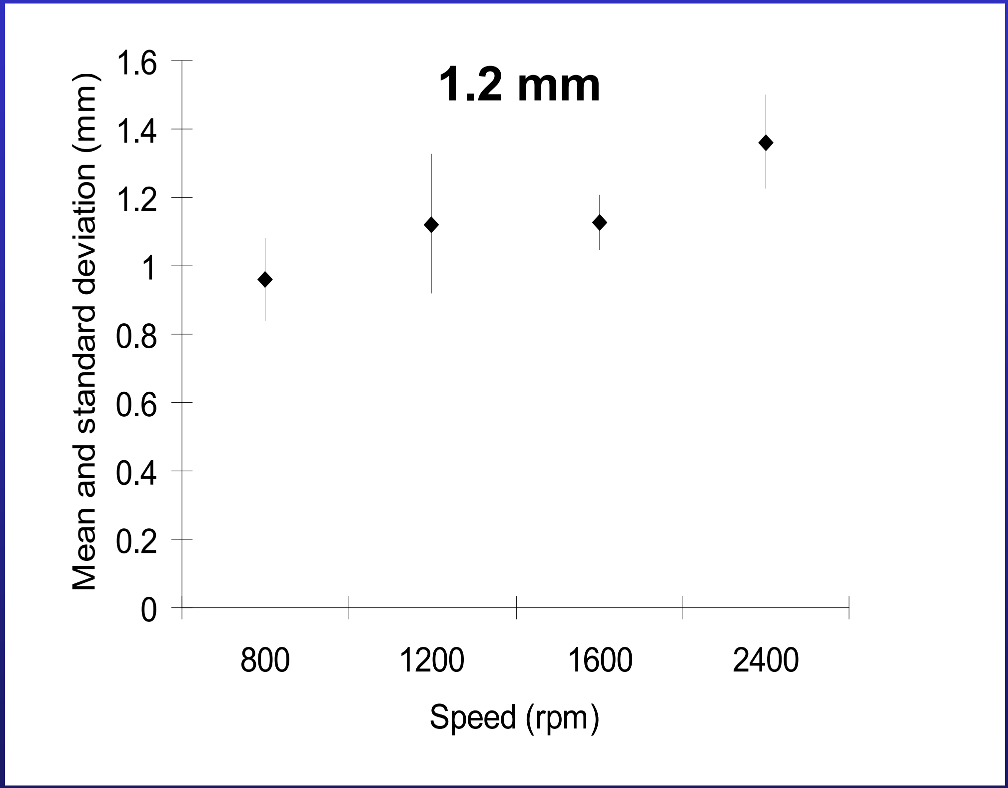
UNSW measurement of pre-whitened signal



Now evident that entry signal is lower frequency than exit signal. Proposed that entry event is a step response in acceleration from sudden change in radius of path. Exit event is a step in velocity (direction); therefore an impulse response in acceleration.

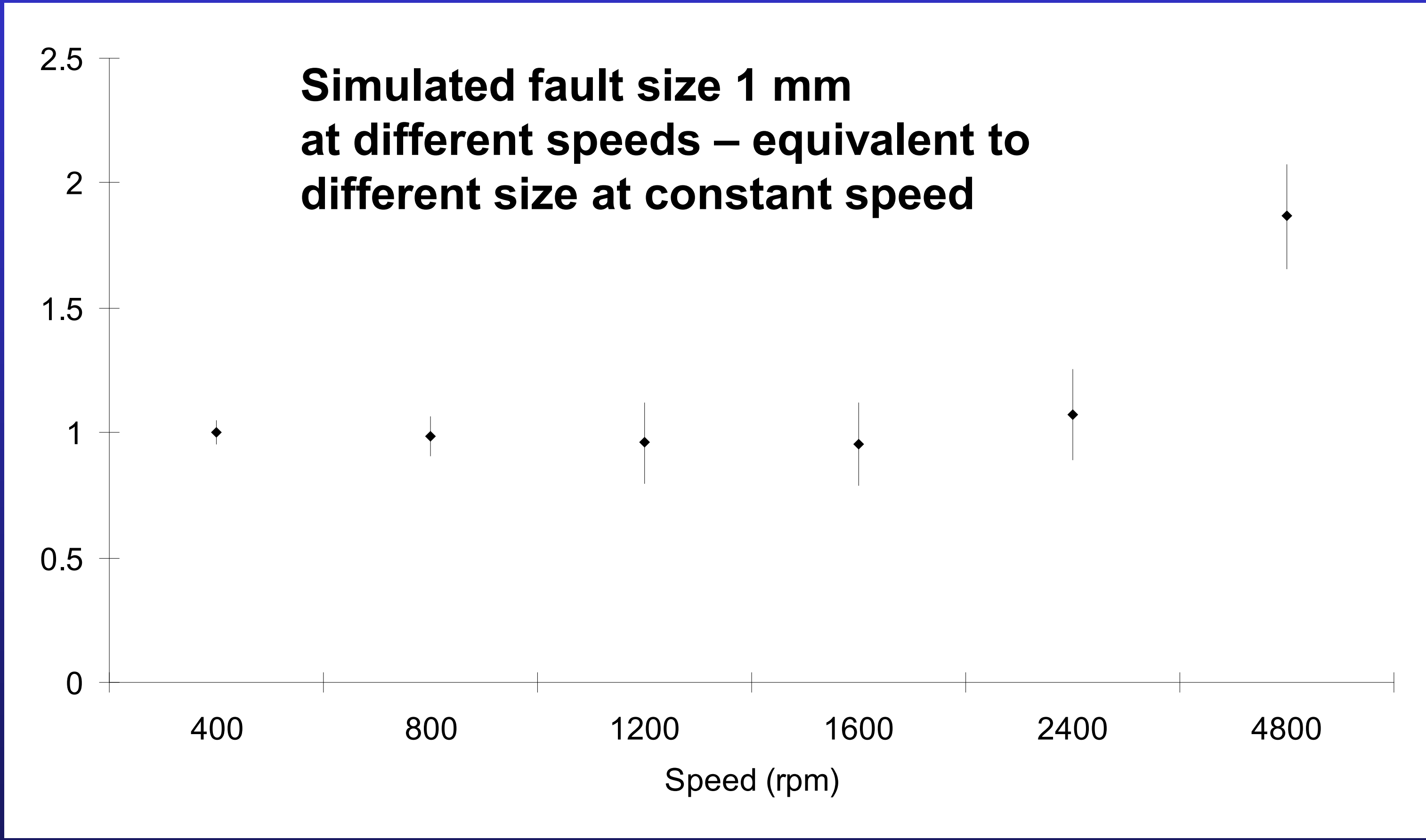
Direct measurement of entry/exit spacing measured signals





Systematic increase with speed (not yet explained)

Direct measurement of entry/exit spacing simulated signals



No systematic increase with speed but limitation on minimum spacing

CONCLUSION

- Prognostics is the least developed of the three phases of condition monitoring, detection, diagnosis, prognosis
- In simpler cases, trending of the RMS level of a band dominated by the bearing signal is satisfactory
- In more complex cases it is necessary to separate the bearing signal from masking signals – separation techniques exist
- Bearing fault signals characterised by impulsiveness in the early stages – (spectral) kurtosis useful
- Trending is not always monotonic to failure
- Technique emerging to directly measure the spall size by difference between entry and exit times